Comment on "Possible Explanation of the Solar-Neutrino Puzzle"

In a recent Letter[1] Bethe has pointed out that the mechanism of matter-enhanced neutrino oscillations[2] could provide a solution to the solar-neutrino problem. In particular one can estimate[3] that the mass difference between the electron neutrino and another neutrino should be about 1.1×10^{-4} eV^2. It is usually assumed that the electron neutrino mixes with the muon neutrino. In this context it is found[1] that even very small mixing angles $\theta_v > 0.0065$ can account for the deficiency of a solar-neutrino signal.

Terrestrial experiments are already sensitive to a region of parameters outlined above and real-time solar-neutrino experiments can study the region of parameters ($\Delta m^2 \sim 10^{-6}$ eV^2) suggested by an alternative solution.[4]

In particular the same resonance condition that enhances the amplitude in the sun produces an enhancement as neutrinos travel through the Earth. The density of the Earth ranges from 2.8 to over 12 g/cm^3 through the core. This gives the resonance condition for neutrino energies of from 550 to 150 MeV for the relatively large mass difference considered in Ref. 1. The alternative solution[4] satisfies the resonance condition for 0.1 MeV $< E_v <$ 50 MeV depending on the exact value of Δm^2. This is the range of energies present in solar neutrinos and the *rotation of the Earth should produce a modulation of the solar-neutrino signal.* The solution itself may need some modification to reflect the effect on previous measurements.

Data exist on neutrino propagation through the Earth[5,6] for $E_v > 200$ MeV and in some cases for $E_{\nu_e} > 30$ MeV. Atmospheric neutrinos[5] are the result of the decay of particles produced by cosmic-ray interactions in the atmosphere. Muon neutrinos outnumber electron neutrinos by a factor[6] of 3.1. Primarily because of cross-section differences, neutrino interactions outnumber antineutrino interactions by about a factor of 3. The energy region[6] 200–500 MeV contains 58% of the ν_μ data.

Such a situation is accurately sensitive to oscillations of $\nu_\mu \rightarrow \nu_e$ and less sensitive to $\nu_e \rightarrow \nu_\tau$ oscillations since these would show up only as a deficiency in the smaller ν_e signal. But all oscillations are, in principle, observable.

The source is approximately uniformly distributed. Upward-going neutrinos having traversed matter can be directly compared with those from above.

A rough limit may be obtained from data already available. The Kamiokande group[6] has presented its data in four bins of equal solid angle and in bins 100 MeV wide, as shown in the following table:

$\cos\theta_z$	M events	S events
1.0–0.5 (up)	6	1
0.5–0	5	3
0–(−0.5)	3	1
−0.5–(−1.0) (down)	9	2

We compare muons (M) to electrons (S) from the ν_μ detection threshold (161 MeV) to about 400 MeV.

There are in total 15 events going upward and 15 downward. Using the downward sample as a standard we can calculate the rate of $\nu_\mu \rightarrow \nu_e$ from both the decrease in ν_μ and the increase in ν_e. They agree and give a rate

$$R(\nu_\mu \rightarrow \nu_e) = 0.11 \pm 0.30 \leq 0.49 \text{ (90\% C.L.)}.$$

This can be converted to a limit on the vacuum mixing angle: $0.2 < \sin\theta_v < 0.6$ is excluded at 90% confidence level. These limits may easily be improved as more data become available and by application of different cuts to probe different regions of parameter space.

For large mixing angles ($\cos 2\theta_v << 1$) the energy of the resonance condition decreases and may become hard to see. Below ν_μ threshold the effect could only be observed as an enhancement in the ν_e rate. But large mixing angles would obviate the need for this solution. Small mixing angles correspond to long oscillation lengths,

$$l_m = 2\pi E_v / \Delta m^2 \sin 2\theta_v.$$

These become hard to observe when the oscillation length is very much larger than the path length, $\sim 10^7$ m, available to experiments. In that case, high statistics are needed to observe the small effect.

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John M. LoSecco
Department of Physics
University of Notre Dame
Notre Dame, Indiana 46556

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[2] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).

[3] I would like to thank W. Fowler for pointing this out.

[4] S. P. Rosen and J. M. Gelb, Phys. Rev. D **34**, 969 (1986).

[5] J. LoSecco *et al.*, in *Proceedings of the Nineteenth International Cosmic Ray Conference,* edited by F. C. Jones (Goddard Space Flight Center, Greenbelt, MD, 1985), Vol. 8, p. 116; G. Battistoni *et al., ibid.*, p. 271.

[6] M. Koshiba, talk presented at the Aspen Winter Conference on Particle Physics, Aspen, 1986 (to be published).