Fermilab ν Committee
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If MiniBooNE Sees a Signal

Boris Kayser

Bethe : Mixing angles are small.

Experiment : Only the small ones are.

Most theorists : MiniBooNE will refute LSND.

MiniBooNE : Stay tuned !!

A signal in MiniBooNE would mean rich opportunities.

We need to be prepared.

If MiniBooNE Sees a Signal

(B.K. & S. Parke)

Suppose MiniBooNE sees excess ν_e events in its $\nu_\mu + (1\%)\,\nu_e$ beam.

1. Is the ν_e signal consistent with the LSND $\bar{\nu}_\mu \to \bar{\nu}_e$ signal?

2. Do the signals in ν_μ and $\bar{\nu}_\mu$ beams coincide? If not, ~~CP~~ or ~~CPT~~.

3. Is the ν_e signal a function of L/E (proper time in ν rest frame)?

4. If yes, is its L/E – dependence that of decay or oscillation?

5. If oscillation, how many frequencies Δm^2_{ij} are involved? What are they? Are they the same for ν and $\bar{\nu}$? (If not, ~~CPT~~.)

6. If there is no indication of ~~CPT~~, what is the (bigger than 3x3) mixing matrix $\mathcal{U}$?

7. What are the implications for ~~CP~~?

2, 5, 7 : $\bar{\nu}_\mu$ running

3 – 7 : Additional detector(s)

Short-Base-Line Oscillation to ν_τ

$$\text{SBL} \equiv L/E \sim 1 \text{ km/GeV}$$

Would $\nu_\mu \to \nu_\tau$ and/or $\nu_e \to \nu_\tau$ be illuminating?

{Modest ν Fact or β Beam

For ν_τ appearance, would need to work above τ threshold. Higher E and higher L, for fixed L/E.

Over a SBL,

$$1 - P(\nu_\mu \to \nu_\mu) \lesssim (5\text{-}10)\% \quad \text{(CDHS)}$$

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) \lesssim (5\text{-}10)\% \quad \text{(Bugey)}$$

4) From LSND, we know –

$$P(\overset{(-)}{\nu}_\mu \leftrightarrow \overset{(-)}{\nu}_e) \sim 0.25\%.$$

If –

$$1 - P(\nu_\mu \to \nu_\mu) = P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\tau) + P(\nu_\mu \to \nu_s)$$
$$\sim 5\%,$$

$P(\nu_\mu \to \nu_\tau)$ and $P(\nu_\mu \to \nu_s)$ can each be a few percent.

Similarly for $P(\nu_e \to \nu_\tau)$ and $P(\nu_e \to \nu_s)$.

$\nu_{\mu,e}$ disappearance and ν_τ appearance (or constraint via NC measurement) could both be interesting.

Implications for θ_{13}

If LSND oscillations are confirmed, θ_{13} is not quite so central a parameter.

If $\nu_\mu \to \nu_e$ within 500 m (MiniBooNE), then LBL probes of "$\sin^2\theta_{13}$"† via $\nu_\mu \to \nu_e$ are contaminated by the SBL $\nu_\mu \to \nu_e$.

If at reactor energies $\bar{\nu}_e \to \bar{\nu}_{\tau,s}$ at the few percent level within a few meters, reactor probes of $\sin^2\theta_{13}$ via $\bar{\nu}_e$ disappearance are also contaminated.

†The strength of $\nu_\mu \leftrightarrow \nu_e$ at the Δm^2_{atm} scale.

If there are 4 neutrino mass eigenstates, there are several important small mixings.

Implications for Theory

Solar + atmospheric + LSND oscillations

$\Rightarrow$ ~~CPT~~ or $\geq 4\,\nu$ species

~~CPT~~: We must go beyond local, relativistic quantum field theory

$\geq 4\nu$: If there are N mass eigenstates

ν_i, $N > 3$, —

U is $N \times N$

U contains —

$\frac{N(N-1)}{2}$ Mixing Angles

$\frac{(N-1)(N-2)}{2}$ Dirac ~~CP~~ Phases

$(N-1)$ Majorana ~~CP~~ Phases

(No effect on oscillation)

There are $N-1$ independent $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$.

3 linear combinations of the ν_i are the active neutrinos, ν_e, ν_μ, ν_τ

The remaining $N-3$ linear combinations orthogonal to ν_e, ν_μ, ν_τ are sterile neutrinos, $\nu_{s_1}, \nu_{s_2}, \ldots$

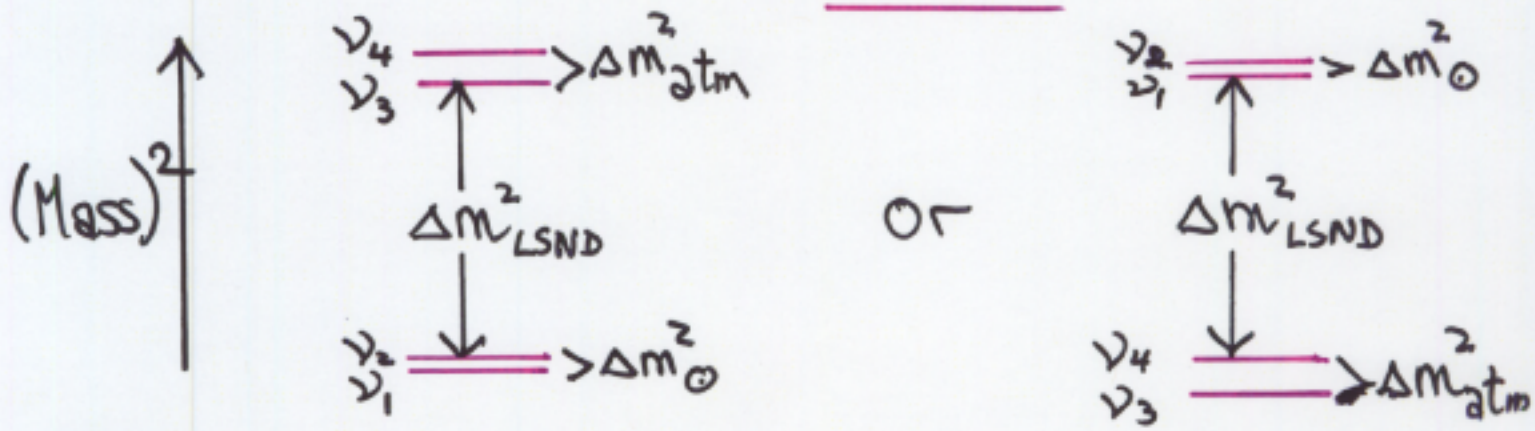
The neutrino world would be very rich.

Implications for LBL Fermilab Experiments

Assume we have a 4-neutrino spectrum.

The spectrum can look like–

2+2

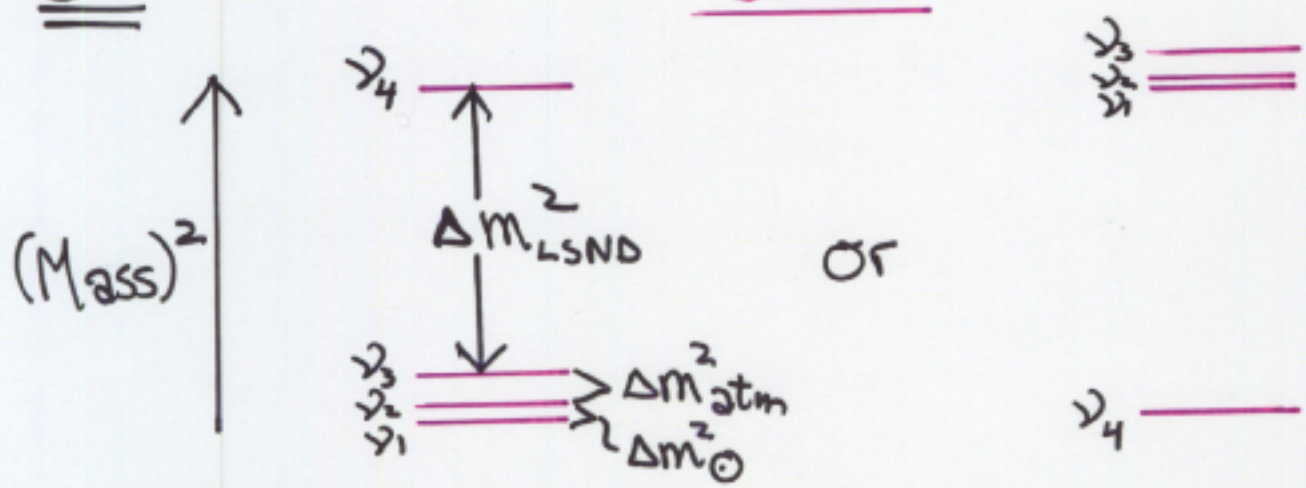


The ν_e (ν_μ) content is >97% in the solar (atm) pair.

(Bugey, CHOOZ, CDHS)

or

3+1



The ν_e and ν_μ content is >97% in the close-spaced trio.

(Bugey, CHOOZ, CDHS)

2+2 spectra in general demand considerable sterile neutrino production in solar and/or atm oscillations.

3+1 spectra escape this prediction if ν_4 is largely sterile.

Implications for MINOS-Off Axis

2+2

$$1 - P(\nu_\mu \to \nu_\mu) = \sin^2 2\theta_{atm} \sin^2 \Delta_{atm}$$

$4|U_{\mu 3}|^2 |U_{\mu 4}|^2$

$\Delta m^2_{atm} \frac{L}{4E}$

$$P(\nu_\mu \to \nu_\tau) = \cos^2\alpha \sin^2 2\theta_{atm} \sin^2 \Delta_{atm}$$

$\cos^2\alpha \to 0.81$ (Super-K)

$$P(\nu_\mu \to \nu_e) \simeq 0$$

3+1

$$\langle 1-P(\nu_\mu \to \nu_\mu)\rangle_E \cong \overbrace{4|U_{\mu 3}|^2\left[1-|U_{\mu 3}|^2\right]\langle \sin^2\Delta_{atm}\rangle_E}^{\text{Usual 3-}\nu\text{ result}}$$

$$\underbrace{+\,2|U_{\mu 4}|^2\left[1-2|U_{\mu 3}|^2\langle \sin^2\Delta_{atm}\rangle_E - |U_{\mu 4}|^2\right]}_{\text{Correction term}}$$

The correction term is $\mathcal{O}$[Few Percent].

- But its sign is uncertain:

  What exactly is $\langle \sin^2\Delta_{atm}\rangle_E$?

  Is $|U_{\mu 3}|^2$ on the "light" or the "dark" side of maximal?

The extraction of $|U_{\mu 3}|^2$ ["$\sin^2\theta_{atm}$"] will be affected.

III Implications for $\not{CP}$

$\not{CP}$ in ν oscillation requires at least 3 nondegenerate ν_i.

When there are only 3 ν_i, $\not{CP} \propto \Delta m^2_\odot$

When there are 4 ν_i, there are new $\not{CP}$ effects that remain even when $\Delta m^2_\odot \to 0$.

Where are these new effects most significant?

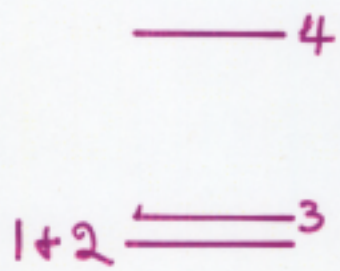
[3] For either a 2+2 or 3+1 spectrum, if we neglect $m_2^2 - m_1^2 \equiv \Delta m_\odot^2$ and small matter effects,

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) = 4\{|U_{\mu 4}U_{e4}|^2 \sin^2\Delta_{41} + |U_{\mu 3}U_{e3}|^2 \sin^2\Delta_{31}$$
$$+ 2|U_{\mu 4}U_{e4}U_{\mu 3}U_{e3}| \sin\Delta_{41} \sin\Delta_{31} \cos(\Delta_{43} \pm \delta_{43})\}.$$

Here,

$$\Delta_{ij} \equiv \Delta m_{ij}^2 \frac{L}{4E} \quad \text{and} \quad \delta_{43} \equiv \arg(U_{\mu 4}U_{e4}^* U_{\mu 3}^* U_{e3}).$$

Example: 3+1



$\Delta_{41} = \Delta_{LSND}$

$\Delta_{31} = \Delta_{atm}$

Work where $\Delta_{atm} = \Delta_{31} = \frac{\pi}{4}$.

$$\langle -2 \sin\Delta_{41} \sin\Delta_{31} \sin\Delta_{43} \sin\delta_{43} \rangle_E$$
$$= \langle -\tfrac{1}{2}[\sin 2\Delta_{43} + \sin 2\Delta_{31} - \sin 2\Delta_{41}] \rangle_E \sin\delta_{43}$$
$$\cong -\frac{1}{2} \sin\delta_{43}$$

$\not{CP}$ in Oscillation to ν_τ

In $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$, $\not{CP}$ can be a large fraction of a small oscillation.

$P(\nu_\mu \to \nu_\tau)$ in Long (Atmospheric) Base Line experiments will be large. Can $\not{CP}$ be a large fraction of that?

Unfortunately, no.

15

3+1

Large atmospheric oscillation

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau) = 4\Big\{|U_{\mu 4}U_{\tau 4}|^2 \sin^2\Delta_{41} + |U_{\mu 3}U_{\tau 3}|^2 \sin^2\Delta_{31}$$

$$+ 2|U_{\mu 4}U_{\tau 4}U_{\mu 3}U_{\tau 3}| \sin\Delta_{41} \sin\Delta_{31} \cos(\Delta_{43} \overset{+}{(-)} \delta'_{43})\Big\}$$

Small elements

New phase

∴ CP effects are a small fraction of the total oscillation.

2+2

$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \\ s \end{array} \begin{array}{c} \begin{array}{cccc} \nu_1 & \nu_2 & \nu_3 & \nu_4 \end{array} \\ \begin{bmatrix} \sim & \sim & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & \sim & \sim \\ \sim & \sim & \sim & \sim \\ \sim & \sim & \sim & \sim \end{bmatrix} \end{array} ; \quad \begin{array}{l} |U_{e3}|^2 + |U_{e4}|^2 < .0 \\ |U_{\mu 1}|^2 + |U_{\mu 2}|^2 < .0 \end{array}$$

If we set $U_{e3} = U_{e4} = U_{\mu 1} = U_{\mu 2} = 0$, all (Dirac) $\not{CP}$ phases can be removed from U.

Then there is no $\not{CP}$ in ν oscillation.

$\therefore$ $\not{CP}$ effects in any oscillation channel are suppressed by the small elements in U.

Summary

Observation of a signal in MiniBooNE would have broad implications:

- Our physics picture would change
- Further SBL experiments would be important.
- The interpretation of LBL and reactor experiments would change. The optimum strategy for these experiments would change.