The Neutrino Scene

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June 3, 2004

Evidence For Flavor Change

Neutrinos	Evidence of Flavor Change
Solar	Compelling
Reactor (L ~ 180 km)	Very Strong
Atmospheric	Compelling
Accelerator (L = 250 km)	Interesting
Stopped μ^+ Decay (LSND, L ≈ 30 m)	Unconfirmed

Solar Neutrinos

Nuclear reactions in the core of the sun produce ν_e. Only ν_e.

Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

$$\nu_{sol}\, d \rightarrow e\ p\ p \ \Rightarrow \phi_{\nu_e}$$

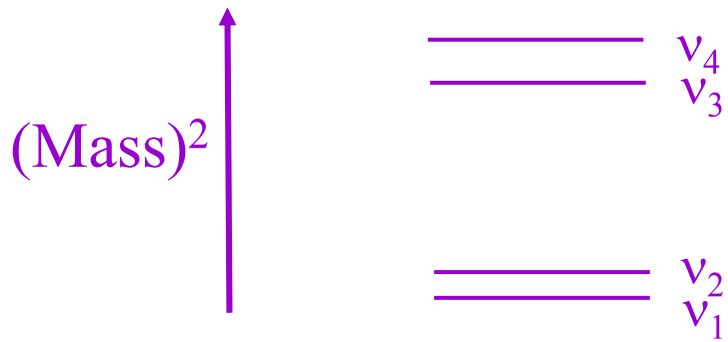
$$\nu_{sol}\, d \rightarrow \nu\ n\ p \ \Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

From the two reactions,

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.306 \pm 0.026\ (\text{stat}) \pm 0.024\ (\text{syst})$$

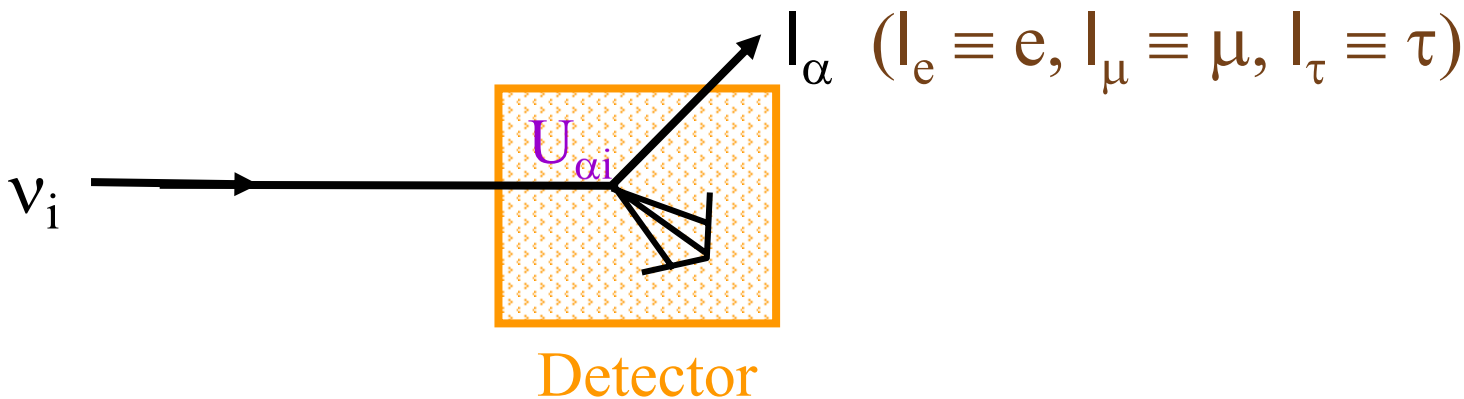
Clearly, $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$. Neutrinos do change flavor.

There is some spectrum of 3 or more neutrino mass eigenstates ν_i:



Mass $(\nu_\iota) \equiv m_i$

ν_e, ν_μ, and ν_τ are mixtures of these mass eigenstates.



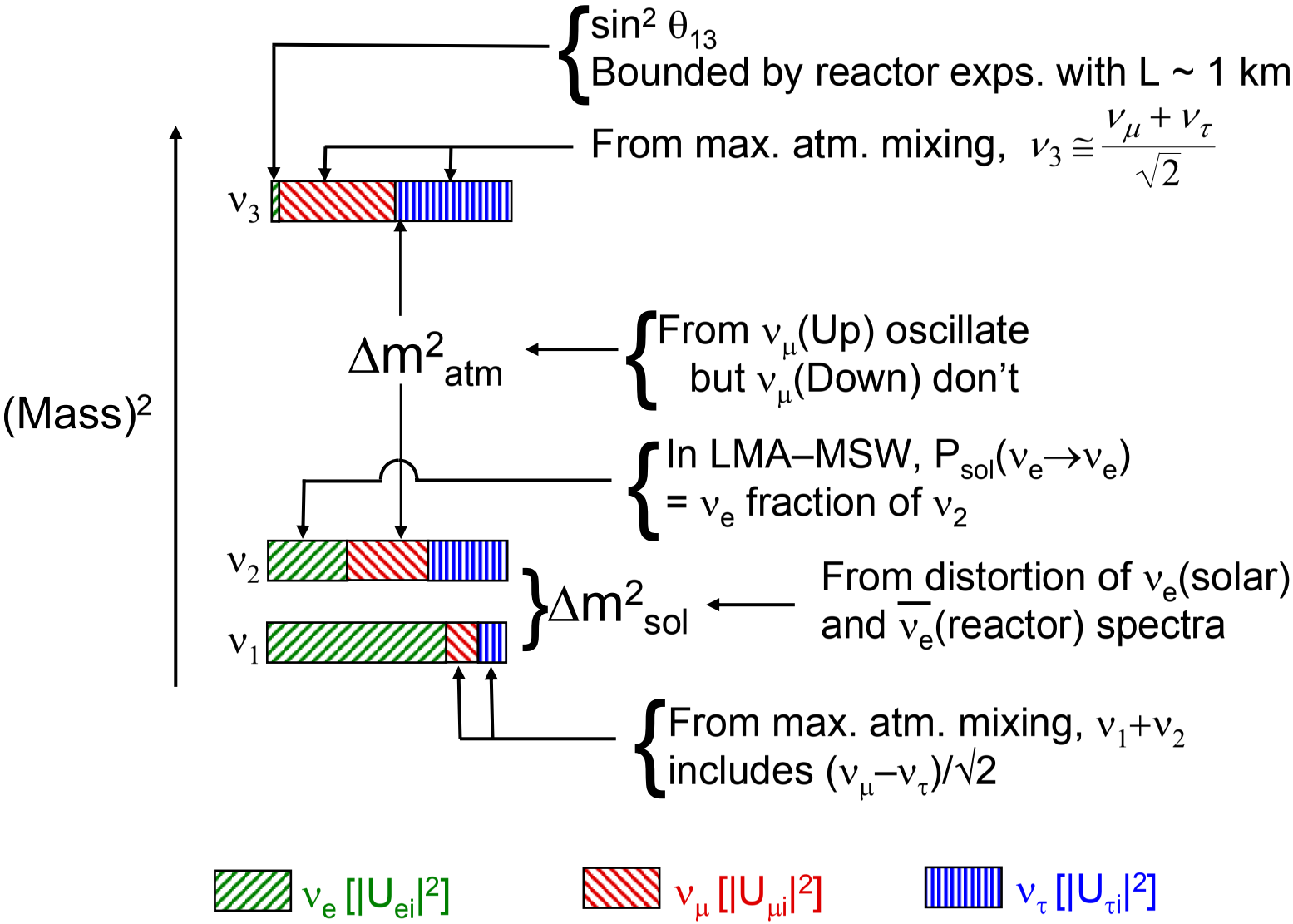
U is the Leptonic Mixing Matrix.

What Have We Learned?

If LSND is confirmed, there are at least 4 neutrino species.

If LSND is not confirmed, nature may contain only 3 neutrinos.

Then, from the existing data, the neutrino spectrum looks like —


sin² θ13
Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, $\nu_3 \cong \frac{\nu_\mu + \nu_\tau}{\sqrt{2}}$
ν3
(Mass)²
Δm²atm
From νμ(Up) oscillate
but νμ(Down) don't
In LMA–MSW, Psol(νe→νe)
= νe fraction of ν2
ν2
ν1
Δm²sol
From distortion of νe(solar)
and ν̄e(reactor) spectra
From max. atm. mixing, ν1+ν2
includes (νμ–ντ)/√2
νe [|Uei|²]
νμ [|Uμi|²]
ντ [|Uτi|²]

The Mixing Matrix

The flavor content picture shows the $|U_{\alpha i}|^2$, but not the signs or phases of the $U_{\alpha i}$.

Atmospheric Cross-Mixing Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Majorana $\not{CP}$ phases

$\theta_{12} \approx \theta_{sol} \approx 32°$, $\theta_{23} \approx \theta_{atm} \approx 35\text{-}55°$, $\theta_{13} \lesssim 15°$

δ would lead to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. $\not{CP}$

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.

— The Future —
What We Would Like to Find Out

- How many different kinds of neutrinos are there?
- What are the masses of the neutrinos?
- What implications do neutrinos and solar-physics/astrophysics/cosmology have for each other?
- Are neutrinos their own antiparticles?

- How extensive is the mixing of different types of neutrinos?
- Do neutrino interactions violate CP?
- Are there surprises, such as large electromagnetic interactions from extra dimensions?
- What can neutrinos tell us about physics at the grand unification scale?
- Are neutrinos responsible for the matter-antimatter asymmetry of the universe?

The American Physical Society Divisions of —

Particles and Fields
Nuclear Physics
Astrophysics
Physics of Beams

are sponsoring a year-long study, aimed at laying the groundwork for a sensible future program to answer the open questions.

To quote the Charge—

"The Study will lay scientific groundwork for the choices that must be made during the next few years."

Working Groups — The Central Element

Each working group is defined by an experimental approach.

The groups and their leaders —

Solar and Atmospheric Neutrino Experiments

John Bahcall <jnb@ias.edu>, Josh Klein <jrk@physics.utexas.edu>

Reactor Neutrino Experiments

Gabriela Barenboim <gabriela@fnal.gov>, Ed Blucher <blucher@hep.uchicago.edu>

Superbeam Experiments and Development

Bill Marciano <marciano@bnl.gov>, Doug Michael <michael@hep.caltech.edu>

Neutrino Factory and Beta Beam Experiments and Development

Stephen Geer <sgeer@fnal.gov>, Michael Zisman <mszisman@lbl.gov>

Neutrinoless Double Beta Decay and Direct Searches for Neutrino Mass

Steve Elliott <elliotts@lanl.gov>, Petr Vogel <pxv@caltech.edu>

What Cosmology/Astrophysics and Neutrino Physics can Teach Each Other

Steve Barwick <barwick@HEP.ps.uci.edu>, John Beacom <beacom@fnal.gov>

Theory Discussion Group

Rabi Mohapatra <rmohapat@physics.umd.edu>

Conclusions and recommendations in a report to be completed by end of August.

Final General Meeting —

Snowmass, June 28-30

See www.interactions.org/neutrinostudy

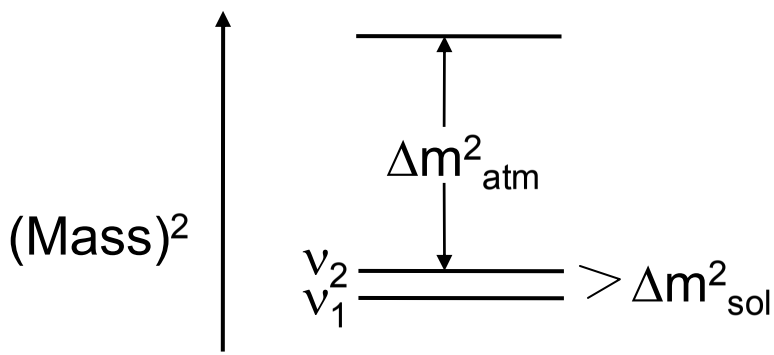
All are welcome!

Methods and Payoffs

Emphasis on questions whose answers will come from accelerator and reactor experiments.

Assume first that there are only 3 neutrino mass eigenstates.

✠ What is the neutrino mass spectral pattern?



Today: $1.9 \times 10^{-3} < \Delta m^2_{atm} < 3.0 \times 10^{-3}\ eV^2$ (90% SuperK)

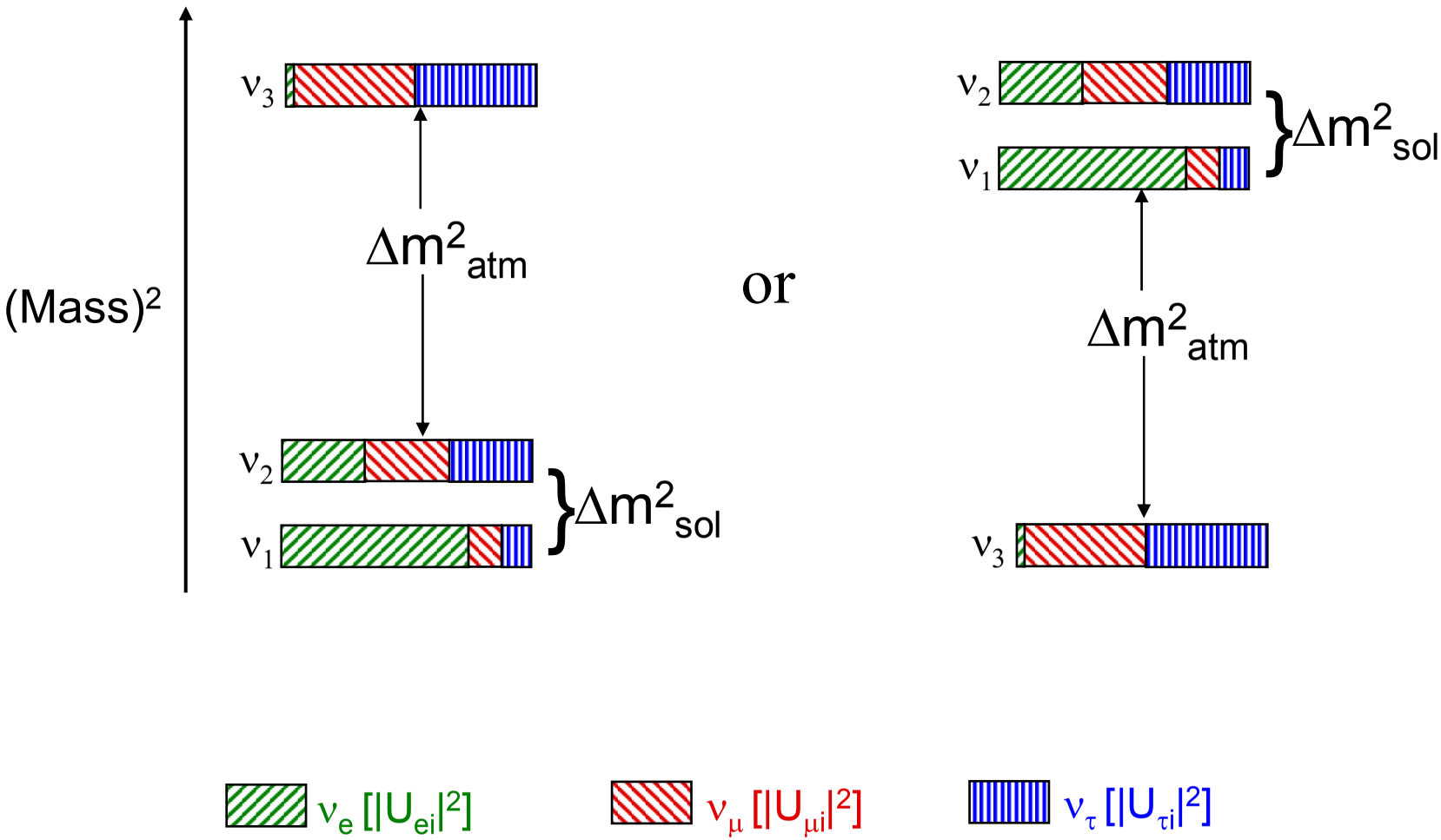
Tomorrow: ? $< \Delta m^2_{atm} <$? (MINOS)

Is the spectral pattern or ?

Generically, SO(10) grand unified models predict .

is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

$\overset{(-)}{\nu}$ behavior in earth matter can distinguish between and .


(Mass)²
ν3
ν2
ν1
Δm²atm
Δm²sol
or
ν2
ν1
ν3
Δm²sol
Δm²atm
νe [|Uei|²]
νμ [|Uμi|²]
ντ [|Uτi|²]

In matter, at superbeam energies,

$$\Delta m^2_{atm} \rightarrow \Delta m^2_{eff} \approx \Delta m^2_{atm} \times \left[1 - S \frac{E}{12\ \text{GeV}}\right]$$

$\text{Sign}[m^2(\text{—}) - m^2(\text{═})]$

⇒ Larger E is better

But want L/E to correspond to ~ peak of oscillation

⇒ Larger E should be matched by larger L

Determining whether the spectrum is like or like could be a unique contribution of NOνA or its proton-driver-enhanced successor, or of a Brookhaven Long Base Line program.

At NOνA, with a 2nd detector, the determination would be possible for $\sin^2 2\theta_{13}$ almost down to 0.01.

(The NOνA collaboration)

✠What is θ_{13} ?

$\sin^2 \theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3. ν_3 is at one end of Δm^2_{atm}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm}, and involving ν_e.

Possibilities

Reactor $\overline{\nu}_e$ disappearance while traveling L ~ 1 km.

Accelerator $\nu_\mu \rightarrow \nu_e$ or $\nu_e \rightarrow \nu_\mu$ while traveling L > Several hundred km.

Accelerator LBL measurements depend on θ_{13}, θ_{atm}, Sign (Δm^2_{atm}), and δ.

They can probe all of these quantities.

Reactor experiments depend only on θ_{13}. Thus, they can measure θ_{13} cleanly.

Sensitivity:

Experiment	$\sin^2 2\theta_{13}$
Present CHOOZ bound	0.2
Double CHOOZ	0.03
Future US experiment (Detectors at ~200 m and ~ 1.5 km)	0.01

Sensitivity needed as part of the overall program:
~ 0.01

Other measurements: Neutrino magnetic moment, the anomalous Weinberg angle

✠Do neutrino interactions violate CP?

Look for —

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \neq P(\nu_\mu \rightarrow \nu_e) \qquad \text{(Superbeam)}$$

or

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) \neq P(\nu_e \rightarrow \nu_\mu) \qquad \text{(} \nu \text{ Factory)}$$

Must separate CP violation from matter effects.

Facility	Can establish $\not{C}\not{P}$ if $\sin^2 2\theta_{13}$ exceeds
Superbeam from proton driver	10^{-2}
ν factory	10^{-4}

We can exist only because

Matter >> antimatter

in the universe.

$\not{C}P$ in ν oscillation would be evidence that the Matter >> antimatter asymmetry arose from

Leptonic — not Quark or Squark —

$\not{C}P$ in the early universe.

✠Are there more than 3 neutrino mass eigenstates?

MiniBooNE can confirm or refute LSND.

If MiniBooNE running with ν sees no signal, it will not have tested LSND unless it runs with $\bar{\nu}$.

If MiniBooNE (ν and/or $\bar{\nu}$) sees a signal —

- How many additional neutrinos are there?
- What are the splittings Δm^2?
- How should reactor and LBL experiments be interpreted?
- Are there new, Short-Base-Line $\not{CP}$ effects?

An additional detector would be called for.

Conclusion

Neutrino physics presents us with exciting opportunities.

Fermilab could play a leading role in the neutrino program of the future.