Neutrino mass and mixing parameters - a short review -

Eligio Lisi
INFN, Bari, Italy

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Outline:

• Overview of $3\nu$ mass-mixing parameters
• Constraints from $\nu$ oscillation searches
• Constraints from non-oscillation searches
• Combining oscill. & non-oscill. $\nu$ observables
• Beyond the standard $3\nu$ scenario (LSND)
• Conclusions

Organizers’ request: “Talk should be a short introduction aimed at PhD students in experimental (non-neutrino) particle physics”

→ I shall skip all refs. or details for $\nu$ experts/theorists, with apologies to colleagues (for more info, see Proceedings or ask me)
3ν mixing

- Neutrinos mix (as quarks do):
  \[ (\nu_e, \nu_\mu, \nu_\tau)^T = U (\nu_1, \nu_2, \nu_3)^T \]

- The standard rotation ordering of the CKM matrix for quarks happens to be useful also for neutrinos:

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

... but with very different angles:

\[
s_{23}^2 \sim 0.5
\]

\[
s_{13}^2 < \text{few } \%\%
\]

\[
s_{12}^2 \sim 0.3
\]

- Only if \( s_{13}^2 \neq 0 \) one can hope to probe the CP-violating phase \( \delta \)

(“holy grail” of future ν oscillation experiments ⇒ see Kayser’s talk)
3ν mass$^2$ spectrum and flavor content ($\nu_e, \nu_\mu, \nu_\tau$)

Abs. scale | Normal hierarchy | Inverted hierarchy | mass$^2$ splittings
---|---|---|---
$\mu^2$ | $\nu_3$ | $\nu_3$ | $+\Delta m^2$
$
u_2$ | $\nu_1$ | $-\Delta m^2$

Absolute mass scale $\mu$ unknown [but $< O(eV)$]

Hierarchy $[\text{sign}(\Delta m^2)]$ unknown

$\nu_e$ content of $\nu_3$ unknown [but $< \text{few\%}$]

$\delta m^2 \simeq 8.0 \times 10^{-5} \text{ eV}^2$ ("solar" splitting)

$\Delta m^2 \simeq 2.4 \times 10^{-3} \text{ eV}^2$ ("atmospheric" splitting)
3ν oscillations

Flavor is not conserved as neutrinos propagate

\[ U \neq 1 \Rightarrow \]

\[ m_i \ll E_i \Rightarrow \]

\[ E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \]

\[ \Delta E \Delta t \sim 1 \Rightarrow \]

Oscill. phase:

\[ 1.27 \frac{|m_i^2 - m_j^2| (\text{eV}^2)}{E (\text{GeV})} L (\text{km}) \sim O(1) \]

Two macroscopic oscillation lengths governed by \( \delta m^2 \) and \( \Delta m^2 \), with amplitudes governed by \( \theta_{ij} \). Leading expt. sensitivities:

- \( (\Delta m^2, \theta_{23}, \theta_{13}) \) Atmospheric \( \nu \), K2K long baseline accelerator \(^{(a)}\)
- \( (\delta m^2, \theta_{12}, \theta_{13}) \) Solar \( \nu \), KamLAND long baseline reactor \( \nu \) \(^{(b)}\)
- \( (\Delta m^2, \theta_{13}) \) CHOOZ short-baseline reactor \( \nu \) \(^{(a,b)}\)

\(^{(a)}\) \((\nu_1, \nu_2)\) difference weakly probed

\(^{(b)}\) \((\nu_\mu, \nu_\tau)\) difference not probed
Constraints on $(\Delta m^2, \theta_{23}, \theta_{13})$
from SK + K2K + CHOOZ

See talks by Sulak (SK) and Mariani (K2K)
Super-Kamiokande atmospheric $\nu$

\[ E_{\nu} \sim 10^{-1} - 10^{3} \text{ GeV} \quad L \sim 10 - 10^{4} \text{ km} \quad (\text{large } L/E \text{ range}) \]

For $\theta_{13} \sim 0$ and $\delta m^{2} \sim 0$, a very simple formula fits all SK data (+ MACRO & Soudan2)

\[ P(\nu_{\mu} \rightarrow \nu_{\tau}) \simeq \sin^{2} 2\theta_{23} \sin^{2} \left( 1.27 \frac{\Delta m^{2}(\text{eV})^{2} L(\text{km})}{E(\text{GeV})} \right) \]

1st oscillation dip still visible despite large L & E smearing

Strong constraints on the parameters ($\Delta m^{2}$, $\theta_{23}$)
Atmospheric $\nu$ oscillation evidence robust & confirmed with lab-$\nu$ in K2K

Many interesting details depend on theoretical input & subleading effects

Contours at 1, 2, 3$\sigma$ (1 dof). Note linear scale for $\Delta m^2$ and $\sin^2 \theta_{23}$, with 2nd octant of $\theta_{23}$ unfolded
At the $\Delta m^2$ scale of SK+K2K, nonobservation of $\nu_e \rightarrow \nu_e$ in the CHOOZ reactor experiment sets strong upper bounds on $\theta_{13}$.

Growing literature & interest in subleading effects due to $\theta_{13}, \delta m^2, \text{sign}(\Delta m^2), \delta$

But need very significant error reduction to probe them

A challenge for future high-statistics experiments
Constraints on $(\delta m^2, \theta_{12}, \theta_{13})$
from solar $\nu + \text{KamLAND}$

See talks by Sulak (SK), Berger (kamLAND), Miknaitis (new SNO data)
Solar $\nu_e \rightarrow \nu_{e,\mu,\tau}$ vs atmospheric $\nu_\mu \rightarrow \nu_\tau$: matter (MSW) effect

Atmospheric $\nu_\mu$ and $\nu_\tau$ feel background fermions in the same way (through NC); no relative phase change ($\sim$ vacuum-like)

But $\nu_e$, in addition to NC, have CC interaction with background electrons (density $N_e$). Energy difference: $V = \sqrt{2} G_F N_e$

Solar $\nu$ analysis must account for MSW effects in the Sun and in the Earth (Earth matter effects negligible for KamLAND reactor neutrinos)

Solar+KamLAND combination provide evidence for $V_{\text{sun}}$ (not yet for $V_{\text{earth}}$)
Dramatic reduction of the $(\delta m^2, \theta_{12})$ param. space in 2001-2003 (note change of scales)

$Cl+Ga+SK$ (2001)  
$+SNO-I$ (2001-2002)  
$+KamLAND-I$ (2002)  
$+SNO-II$ (2003)  
(+ confirmation of solar model)

Direct proof of solar $\nu_e \rightarrow \nu_{\mu,\tau}$ in SNO through comparison of

CC : $\nu_e + d \rightarrow p + p + e$  
NC : $\nu_{e,\mu,\tau} + d \rightarrow p + n + \nu_{e,\mu,\tau}$  
ES : $\nu_{e,\mu,\tau} + e \rightarrow e + \nu_{e,\mu,\tau}$
... in 2004 (KamLAND-II with revised background): unique Large Mixing Angle solution, and another change of scale...

+ evidence for oscillatory effects in KamLAND reactor L/E spectrum

What about MSW effects?
Exercise: (1) Change MSW potential “by hand,” $V \rightarrow a_{MSW}V$
(2) Reanalyze all data with $(\delta m^2, \theta_{12}, a_{MSW})$ free
(3) Project $(\delta m^2, \theta_{12})$ away and check if $a_{MSW} \sim 1$

Results: with 2004 data, $a_{MSW} \sim 1$ confirmed within factor of $\sim 2$
and $a_{MSW} \sim 0$ excluded → Evidence for MSW effects in the Sun

But: expected subleading effect in the Earth (day-night difference) still below experimental uncertainties.
2005 (last week): new data + detailed analysis from SNO

Previous results basically confirmed

Slightly higher ratio \( CC/NC \sim p(\nu_e \rightarrow \nu_e) \)

Slight shift (<1\( \sigma \) upwards) of allowed range for \( \theta_{12} \)
3ν analysis of 2004 solar+KamLAND data ($\theta_{13}$ free)

Solar and KamLAND data also prefer $\theta_{13} \sim 0$ (nontrivial consistency with SK+CHOOZ)

Bounds on ($\delta m^2, \theta_{12}$) not significantly altered for unconstrained $\theta_{13}$
“Grand Total” from global analysis of oscillation data
Marginalized $\Delta \chi^2$ curves for each parameter (2004)
Numerical ±2σ ranges (95% CL for 1dof), 2004 data:

\[ \delta m^2 \approx 8.0^{+0.8}_{-0.7} \times 10^{-5} \text{ eV}^2 \]

\[ \Delta m^2 \approx 2.4^{+0.5}_{-0.6} \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2 \theta_{12} \approx 0.29^{+0.05}_{-0.04} \quad \text{(SNO '05: 0.29 → 0.31)} \]

\[ \sin^2 \theta_{23} \approx 0.45^{+0.18}_{-0.11} \]

\[ \sin^2 \theta_{13} < \sim 0.035 \]

\[ \text{sign}(\pm \Delta m^2) : \text{ unknown} \]

\[ \text{CP phase } \delta : \text{ unknown} \]

Note: Precise values for \( \theta_{12} \) and \( \theta_{23} \) relevant for model building (see talk by Tanimoto)
Probing absolute $\nu$ masses through non-oscillation searches
Three main tools ($m_\beta$, $m_{\beta\beta}$, $\Sigma$):

1) $\beta$ decay: $m^2_i \neq 0$ can affect spectrum endpoint. Sensitive to the “effective electron neutrino mass”: (most direct method)

$$m_\beta = \left[ c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2 \right]^{\frac{1}{2}}$$

2) $0\nu2\beta$ decay: Can occur if $m^2_i \neq 0$ and $\nu = \nu$. Sensitive to the “effective Majorana mass” (and phases): (several talks this afternoon)

$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

3) Cosmology: $m^2_i \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB+other data. Probes: (see talk by Pastor)

$$\Sigma = m_1 + m_2 + m_3$$
Even without non-oscillation data, the \((m_\beta, m_{\beta\beta}, \Sigma)\) parameter space is constrained by previous oscillation results:

**Significant covariances**

**Partial overlap between the two hierarchies**

**Large \(m_{\beta\beta}\) spread due to unknown Majorana phases**
But we do have information from non-oscillation experiments:

1) $\beta$ decay: no signal so far. Mainz & Troitsk expts: $m_\beta < O(eV)$

2) $0\nu2\beta$ decay, no signal in all experiment, except in the most sensitive one (Heidelberg-Moscow). Rather debated claim.
   Claim accepted: $m_{\beta\beta}$ in sub-eV range (with large uncertainties)
   Claim rejected: $m_{\beta\beta} < O(eV)$.

3) Cosmology. Upper bounds:
   $\Sigma < eV/sub-eV$ range, depending on several inputs and priors. E.g.,
0ν2β claim rejected

Cosmological bound dominates, but does not probe hierarchy yet

0ν2β claim accepted

Tension with cosmological bound
(no combination possible at face value)
But: too early to draw definite conclusions
E.g., if $0\nu2\beta$ claim accepted & cosmological bounds relaxed:

Combination of all data (osc+nonosc.) possible

Complete overlap of the two hierarchies (degenerate spectrum with “large” masses)

High discovery potential in future ($m_\beta$, $m_{\beta\beta}$, $\Sigma$) searches
Many theoretical reasons to go beyond the standard $3\nu$ scenario
A purely experimental reason: the puzzling LSND oscillation claim
$\Delta M^2 \sim O(\text{eV}^2)$ with very small mixing?

Solutions invented so far (new sterile states, new interactions or properties) seem rather "ad hoc" and/or in poor agreement with world neutrino data

If MiniBoone (talk by McGregor) confirms LSND this year, many ideas will be revised, and the neutrino session of Moriond 2006 will be fun!
Conclusions

Great progress in recent years ...

**Neutrino mass & mixing: established fact**
- Determination of \((\delta m^2, \theta_{12})\) and \((\Delta m^2, \theta_{23})\)
- Upper bounds on \(\theta_{13}\)
- Oscillation-induced spectral distortions
- Direct evidence for solar \(\nu\) flavor change
- Evidence for matter effects in the Sun
- Upper bounds on \(\nu\) masses in (sub)eV range

**... and great challenges for the future!**

- Determination of \(\theta_{13}\)
- Leptonic CP violation
- Absolute \(m_\nu\) from \(\beta\)-decay and cosmology
- Test of 0ν2β claim and of Dirac/Majorana \(\nu\)
- Matter effects in the Earth
- Normal vs inverted hierarchy
- Beyond the standard 3\(\nu\) scenario
- Deeper theoretical understanding

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