Neutrino mixing:
Results from accelerator experiments

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Alexander Korzenev (NA61)
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Andre Rubbia (LBNO)
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Abbey Waldron (NOvA)
Michael Wilking (T2K)
Elizabeth Worcester (LBNE)
Outline

• What are the open questions?
• $\nu_\mu$ disappearance
• Anomalies (sterile neutrino?)
• Progress towards precision measurement
• $\nu_e$ appearance
• From now on
Three Flavor Mixing in Lepton Sector

Weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\cos \theta_{ij} = c_{ij}, \sin \theta_{ij} = s_{ij}$$

$$\Delta m^2_{12}, \Delta m^2_{23}, \Delta m^2_{13}$$

$$\Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31}$$

Two free parameters for the three $\Delta m^2$'s.

$$\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{32}$$

$$* \Delta m^2_{ji} = m_j^2 - m_i^2$$
Strange feature of mixing matrix

\[ U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 1.01 & 0.04 \\ 0.008 & 0.04 & 0.89 \end{pmatrix} \quad U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.55 & 0.16 \\ -0.49 & 0.52 & 0.55 \\ 0.20 & -0.65 & 0.70 \end{pmatrix} \]

(writing just magnitude)

- 1999: Upper limit (<11°) by Chooz reactor experiment
- 2011: Indication (2.5σ) of non-zero \( \theta_{13} \) by T2K \( \nu_e \) appearance (1.7σ by MINOS)
- 2012: Evidence of non-zero \( \theta_{13} \) (>5σ) by reactor \( \nu_e \) disappearance (Daya Bay, RENO, Double Chooz) 3.1σ by T2K \( \nu_e \) appearance

Based on PDG 2012

Measured in 2011~2012!
Target of neutrino oscillation experiments

Mixing matrix for leptons

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

\[ (c_{ij} = \cos \theta_{ij}, s_{ij} = \sin \theta_{ij}) \]

**Unknown**

**CP phase**

KEY to understand the origin of matter dominant universe

**Mixing angles**

- \( \theta_{12} = 34^\circ \pm 1^\circ \)
- \( \theta_{23} = 40^\circ + 5^\circ / -2^\circ \)
- \( \theta_{13} = 9.1^\circ \pm 0.6^\circ \)!

**How close to 45\(^\circ\)?**

How close to 45\(^\circ\)?

**Reactor experiments**

Big Impact on 0\(\nu\) double-\(\beta\) decay search (hence on Majorana \(\nu\) confirmation)

**Mass Hierarchy**

**Normal**

- \( \sim 7.6 \times 10^{-5}eV^2 \)
- \( \sim 2.4 \times 10^{-3}eV^2 \)

**Inverted**

- \( \sim 7.6 \times 10^{-5}eV^2 \)
- \( \sim 2.4 \times 10^{-3}eV^2 \)

**OR**

Unknown
Unsolved problems concerning the basic property of neutrino

- Strange features of mixing matrix
- Is CP violated like in the case of quarks?
- Are there only three types of neutrinos?
- Are neutrinos the origin of the matter-dominant universe?
- Why are they so light compared to quarks or charged leptons?
- Are neutrinos Majorana particles?
- Absolute mass
- .....
Oscillation at $L(km)/E(GeV) \sim 500$

**Leading term**

$$
\Delta m_{32} \frac{L}{4E} \sim \Delta m_{31} \frac{L}{4E} \sim \frac{\pi}{2}, \quad \Delta m_{21} \frac{L}{4E} \sim 0
$$

- **$\theta_{23}$**: $\nu_\mu$ disappearance

  $$
P_{\mu \to x} \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E}\right)
$$

  Mainly go to $\nu_\tau$.
  Since $\tau$ production threshold is high (3.5GeV), it disappears in CC current interaction.

- **$\theta_{13}$**: $\nu_e$ appearance

  $$
P_{\mu \to e} \approx \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E}\right)
$$

  $\sim 0.5$
World Long baseline ν oscillation experiments

- OPERA (2008-) ICARUS (2010-) 732km
- MINOS (2005- 2012) 735km
- NOvA (2013-) 819km
- K2K (1999-2004) 250km
- T2K (2010-) 295km
MINOS $\nu_\mu$ disappearance $\nu$ vs. $\bar{\nu}$

Leading measurement of $|\Delta m^2_{\text{atm}}|$ w/ 4.1% precision using accelerator and atmospheric $\nu$'s and $\bar{\nu}$'s.

MINOS $\nu_\mu$ disappearance

- $10.71 \times 10^{20}$ POT $\nu_\mu$ mode
- $3.36 \times 10^{20}$ POT $\bar{\nu}_\mu$ mode
- 37.88 kt-yr Atmospheric

$90\%$ C.L.
- $\nu_\mu$
- $\bar{\nu}_\mu$
- $\nu_\mu + \bar{\nu}_\mu$

Best fit
- $\nu_\mu$
- $\bar{\nu}_\mu$
- $\nu_\mu + \bar{\nu}_\mu$

$|\Delta m^2| - |\Delta m^2| = 0.12^{+0.24}_{-0.26} \times 10^{-3} \text{eV}^2$

MINOS finds consistent values for neutrinos and antineutrino oscillation parameters measured via charged-current disappearance.
Tokai-to-Kamioka (T2K) experiment

\( \sim 0.6 \text{ GeV} \, \nu_\mu \) over 295km

- \( \nu_e \) appearance \( \rightarrow \theta_{13} \)
  - e-like ring, \( \pi^0 \) mass cut etc.
- \( \nu_\mu \) disappearance \( \rightarrow \theta_{23} \)
  - \( \mu \)-like ring etc.

Latest results reported by M. Wilking, EPS HEP2013
T2K data-taking status

Great East Japan Earthquake

6.63 x 10^{20} protons on target (p.o.t.) so far
8.5% of T2K goal statistics
Using data up to Run 3  
Only $\theta_{23} < \pi/4$ region was explored in the results released in February 2013. 
This time $\theta_{23} > \pi/4$ is also considered. Significant difference appeared.

$$P_{\mu \to \mu} \approx 1 - \left( \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \right) \sin^2 \left( \frac{\Delta m^2 L}{4 E_{\nu}} \right)$$

\[ \approx 1 - \left( \cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \right) \sin^2 \left( \frac{\Delta m^2 L}{4 E_{\nu}} \right) \]
Confirmation of $\nu_\mu \to \nu_\tau$ by OPERA

3.8$\sigma$ $\nu_\tau$ appearance by Super-K atmospheric data (Abe et al., PRL 110, 181802 (2013)) from a sample of enhanced $\tau$-like events.

OPERA identifies $\tau$ production in event-by-event basis.

Third $\nu_\tau$ candidate taken in March, 2013

376$\mu$m

Extended sample

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Background</th>
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</thead>
<tbody>
<tr>
<td>$\tau \to h$</td>
<td>0.66</td>
<td>0.045</td>
</tr>
<tr>
<td>$\tau \to 3h$</td>
<td>0.51</td>
<td>0.090</td>
</tr>
<tr>
<td>$\tau \to \mu$</td>
<td>0.56</td>
<td>0.026</td>
</tr>
<tr>
<td>$\tau \to e$</td>
<td>0.49</td>
<td>0.065</td>
</tr>
<tr>
<td>total</td>
<td>2.22</td>
<td>0.23</td>
</tr>
</tbody>
</table>

w/ ~60% of data analyzed

3 observed events in the $\tau \to h$, $\tau \to 3h$ and $\tau \to \mu$ channels

Probability to be explained as a background = $7 \times 10^{-4}$

This corresponds to 3.2 $\sigma$ significance of non-null observation (3.5 $\sigma$ significance with a likelihood approach)
Anomalies at small L/E
(Large $\Delta m^2$ in case of oscillation w/ sterile $\nu$)

Two anomalies

✓ $\nu_e$ excess in $\nu_\mu$ beam by LSND and MiniBooNE
✓ $\nu_e$ disappearance (reactor and Gallium experiments)

MiniBooNE  PRL 110, 161801 (2013)
Anomalies at small L/E
(Large $\Delta m^2$ in case of oscillation with sterile $\nu$)

OPERA 2008-2009 data
A. Pastore, EPS HEP 2013

Search will be continued in $\nu_e$ appearance, $\nu_\mu$ or $\nu_e$ disappearance

Many experimental proposals

- ICARUS/NESSiE at CERN
- MINOS+ using beam from FNAL (running with NOvA)
- Possibly T2K, NOvA
Accelerator Neutrino Physicists have to know about the strong interaction.

- **Flux prediction**
  - ν’s parent particles are produced by hadron production from p+Nucleus interactions

- **Neutrino Interaction**
  - ν+Nucleus interaction is affected by nuclear state
NA61/SHINE Hadron production measurements for the $\nu_\mu$ flux in T2K

Neutrino Flux Prediction in T2K

- Cross sections for $\pi^\pm$, $K^\pm$, $p$ and $K^0_S$
- Cover ~90% of the p phase space of T2K
- Measurement for NuMI target at 120 GeV/c
- New results are released in EPS-HEP2013

Alexander Korzenev EPS-HEP2013
Charged Current Quasi-Elastic scattering by MINERvA (at FNAL MINOS near detector hall)

Cheryl Patrick at EPS-HEP 2013

‘n’ or ‘p’ is in the nucleus and interacting w/ other nucleons.
Data favors TEM (Transverse Enhancement), suggesting initial-state correlations
Latest results of $\nu_e$ appearance

Key mode for CP $\delta$, Mass Hierarchy and $\theta_{23}$ octant
\( \nu_e \) appearance
(complete version in vacuum)

\[
P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cos \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \sin \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \sin^2 \Phi_{21}.
\]

\( C_{ij} = \cos \theta_{ij}, \quad S_{ij} = \sin \theta_{ij} \)

\( \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_v} \)

CP violating term introduced by interference btw. \( \theta_{13} \) and \( \theta_{12} \)

\( \delta \to -\delta \) for \( P(\text{anti-}\nu_\mu \to \text{anti-}\nu_e) \)
\( \nu_e \) appearance at oscillation maximum

\[
P(\nu_\mu \rightarrow \nu_e) \approx 4C_{13}^2 S_{13}^2 S_{23}^2 \left(1 + \frac{2a}{\Delta m^2_{31}}\right) - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin \delta
\]

\[C_{ij} = \cos \theta_{ij}, S_{ij} = \sin \theta_{ij}, \quad \Phi_{ij} = \Delta m^2_{ij} \frac{L}{4E}\]

Matter effect

\[
a = 2\sqrt{2}G_F n_e E = 7.56 \times 10^{-5} \text{eV}^2 \frac{\rho}{\text{g cm}^{-3}} \frac{E}{\text{GeV}}
\]

\( \nu_e \) feels different potential than \( \nu_\mu \) and \( \nu_\tau \) in earth.

\[\delta \rightarrow -\delta, \quad \alpha \rightarrow -\alpha\]

for \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)

This matter effect size corresponds to T2K. (>x2 bigger for NOvA, MINOS and so on.)
MINOS $\nu_e$ appearance

Normal Hierarchy

$\Delta m^2 > 0$

- MINOS Best Fit $\theta_{23} < \pi/4$
- MINOS Best Fit $\theta_{23} > \pi/4$

- 68% C.L. $\theta_{23} < \pi/4$
- 90% C.L. $\theta_{23} < \pi/4$

Inverted Hierarchy

$\Delta m^2 < 0$

MINOS

- $10.6 \times 10^{20}$ POT $\nu$ mode
- $3.3 \times 10^{20}$ POT $\bar{\nu}$ mode

w/ reactor result

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$

PRL 110, 171801(2013)
T2K $\nu_e$ Appearance Updates from 2012

- The background rejection cut is improved using a new SK reconstruction algorithm. Number of BG events reduced from 6.4 to 4.6
- Near detector measurement is improved by using new event categories

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<thead>
<tr>
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<th>2012(*)</th>
<th>2013(now)</th>
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<tbody>
<tr>
<td>POT</td>
<td>$3.010 \times 10^{20}$</td>
<td>$6.393 \times 10^{20}$ ($\sim$Apr 12)</td>
</tr>
<tr>
<td>Bkgs</td>
<td>$3.3 \pm 0.4$</td>
<td>$4.64 \pm 0.51$</td>
</tr>
</tbody>
</table>

- Observed $\nu_e$ cand. Events: 11 vs. 28
- Observed $\nu_e$ app. Significance: $3.1 \sigma$ vs. $7.5 \sigma$

* 2012 result arXiv:1304.0841 (accepted by PRD)
T2K $\nu_e$ appearance

Results

- Fit using electron $(p, \theta)$ distribution
- NOTE! $\sin^2 \theta_{23}$ is fixed to 0.5 in the fit

\[ P(\nu_\mu \rightarrow \nu_e) \propto \]

\[ 4C_{13}^2 S_{13}^2 S_{23}^2 \left( 1 + \frac{2a}{\Delta m_{31}^2} \right) - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin \delta \]

- Best fit value w/ 68% C.L. error @ $\delta_{CP}=0$

  **normal hierarchy:**
  \[ \sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034} \]

  **inverted hierarchy:**
  \[ \sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040} \]

  c.f. reactor results (PDG '12)
  \[ \sin^2 2\theta_{13} = 0.098 \pm 0.013 \]
T2K $\nu_e$ appearance

$\delta_{CP}$ vs. $\sin^22\theta_{13}$
for different $\theta_{23}$

NOTE: PDG'12 $3\sigma$ region for $\sin^2\theta_{23}$: 0.34-0.64

reactor $1\sigma$ region (PDG '12)

$\sin^22\theta_{13} = 0.098 \pm 0.013$
FROM NOW ON
T2K CP violation ($\sin \delta \neq 0$) sensitivity

Simultaneously fitting $\nu_\mu$ disappearance and $\nu_e$ appearance data
Use $\sin^2 2\theta_{13}$ constraint by reactor experiment

No sys. error

100% $\nu$-mode

50%:50% $\nu$-mode:

$\bar{\nu}$-mode

NH

IH

$\Delta \chi^2$ vs $\delta_{CP}$
NuMI beam
• Upgrade from 350 kW to 700 kW
• Expect beam in MI today (=19th)!
• Beam to neutrino line estimated in next
14 kilotons = 28 NOvA Blocks

17 blocks of PVC modules are assembled and installed in place
10.96 blocks are filled with liquid scintillator
4.17 blocks are outfitted with electronics

Expected to complete in April/May 2014
\( \nu_e \) appearance at oscillation maximum

\[
P(\nu_\mu \rightarrow \nu_e) \approx 4C_{13}^2 S_{13}^2 S_{23}^2 \left( 1 + \frac{2a}{\Delta m_{31}^2} \right) - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin \delta
\]

\[
C_{ij} = \cos \theta_{ij}, S_{ij} = \sin \theta_{ij}, \quad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_v}
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Matter effect

\[
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\]

\( \nu_e \) feels different potential than \( \nu_\mu \) and \( \nu_\tau \) in earth.

\[
\delta \rightarrow -\delta, \quad \alpha \rightarrow -\alpha
\]

for \( P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \)
NOvA sensitivity
in case running 3 years in $\nu$-mode
and 3 years in $\bar{\nu}$-mode.
$\sin^2 2\theta_{13} = 0.095$, $\sin^2 2\theta_{23} = 1.00$

NOTE! Sensitivities for CP $\delta$ and 
MH are significantly increased by 
combining T2K($L=295\text{km}$) and 
NOvA($L=819\text{km}$)
LBN Next generation experiments

A short summary of A. Rubbia’s talk “Neutrino Program: the future” given on 20th in Joint ECFA-EPS session.
So just two pages summary, here.

T2K and NOvA would explore the CP phase, $\theta_{23}$ and the Mass Hierarchy w/ O(100) $\nu_e$ appearance (and $\nu_\mu$ disappearance) events. $\sim$10% stat. error. (cf. Max. CP asymmetry $\sim$27%)
We may see something in certain lucky cases.
However, in order to fully explore these problems, we need $\sim$10 times more statistics.
**World LBL Future Project**

LAGUNA-LBNO  130km?~2,300km?
ESS+WC?  540km?

- **Detector options**: 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

**LBNE 1300km**
0.7MW, 10kt LAr → 2.3MW, 35kt LAr

**Hyper-Kamiokande**
- Total Volume: 0.99 Megaton
- Inner Volume (Fiducial Volume): 0.74 (0.56) Megaton
- Outer Volume: 0.2 Megaton
- Inner detector: 90,000 20-inch PMTs, 20% photo-coverage
- Outer detector: 25,000 8-inch PMTs

**Hyper-K 295km**
0.75MW →~2MW
Summary

- $\nu_\mu$ disappearance
  - Confirmed $\nu_\mu \rightarrow \nu_\tau$
  - Precise measurement would answer how close to $45^\circ \theta_{23}$ is.
    (Current PDG 1\sigma region is $38^\circ \sim 45^\circ$)
- Anomalies at small L/E need to be solved.
- In the era of Precision measurement
  - Flux and $\nu$ interaction
- $\nu_e$ appearance
  - Confirmed (T2K 7.5\sigma)
  - The discovery of non-zero $\theta_{13}$ in 2012 is not the end of the story, but is the start of new quest: CP $\delta$, Mass Hierarchy and $\theta_{23}$ octant
  - We may start to see something about CP $\delta$.
- Stay tuned to T2K and NOvA, and the evolution of future projects