Neutrino oscillation: non-accelerator experiments

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Outline

• Solar neutrinos
• Atmospheric neutrinos
• Reactor neutrinos
• Sterile neutrinos
• Summary
Neutrino Oscillation

- If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:

\[
P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E)
\]

Oscillation matrix for 3 generations:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
\begin{pmatrix}
V_{e1} & V_{e2} & V_{e3} \\
V_{\mu1} & V_{\mu2} & V_{\mu3} \\
V_{\tau1} & V_{\tau2} & V_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

- Known parameters: \( \theta_{23}, \theta_{12}, |\Delta M^2_{23}|, \Delta M^2_{12}, \)
- Recent progress: \( \theta_{13} \)
- Unknown parameters: mass hierarchy(\( \Delta M^2_{23} \)), CP phase \( \delta \)
Solar neutrinos

- First indication of neutrino deficit by Homestake exp. (70’s-90’s)
- Confirmed by many Exp.s → multiple solutions of $\theta_{12}$ & $\Delta M^2_{12}$
- Solar neutrino oscillation established (00’s):
  - SuperK: indication of LMA-MSW
  - SNO: missing $\nu_e$ appeared as $\nu_\mu + \nu_\tau$
  - KamLAND: $\theta_{12}$ & $\Delta M^2_{12}$
  - Standard Solar Model established

- Current experiments:
  - Borexino
  - SuperKamiokande

- Main issues:
  - Solar related

- Future experiment:
  - SNO+, XMASS, LENA, JUNO…

Y. Suzuki@ NeuTel’13
Borexino

- **pep neutrinos** are observed for the first time:
  \[ \Phi_{\text{pep}} = 1.6 \pm 0.3 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \]

- Most of the solar \( \nu_e \) components have been seen (except CNO): all in good agreement with SSM and the MSW-LMA solution

- Seasonal variation may be seen: an independent confirmation of solar \( \nu_e \) observation

Results from Phase 2: Rate vs time

ranucci@EPS-HEP’13
Super-Kamiokande

- Thanks to new electronics and tight FV cut, $E_{\text{thresh}} \sim 3.5$ MeV
- Improved $\theta_{12}$ & $\Delta M^2_{12}$ measurements in combination with other solar & KamLAND results:
  
  $$\sin^2 \theta_{12} = 0.304 \pm 0.013,$$
  
  $$\Delta m^2_{21} = 7.45^{+0.20}_{-0.19} \times 10^{-5} \text{eV}^2.$$  

- A $2.7 \sigma$ Day-Night asymmetry is observed: indication of the regeneration of $\nu_e$ as they travel through earth matter
- In agreement with expectation (1 $\sigma$ tension)
Future experiment: SNO+

- Construction almost finished, to be operational next year
  - 780t liquid scintillator (LAB)
  - 9500 PMTs
  - Water shielding
  - Hold down rope net on the 12 m diameter Acrylic vessel

- Physics:
  - Solar neutrinos
    - Better measurement of pep & $^8B$ neutrinos
    - Look for CNO neutrinos
  - Geoneutrinos
  - Supernova neutrinos
  - Double beta decays

McDonald@Neutrino’12
Future experiment: LENA

• The detector:
  – 50 kt liquid scintillator (LAB)
  – 30,000 12” PMT with Winston cone, 30% coverage
  – Water Veto with 4000 8” PMT

• Physics
  – Solar neutrinos
    • CNO neutrinos for solar metallicity
  – Burst Supernova neutrinos
  – Diffused Supernova neutrinos
  – Geo-neutrinos
  – Short baseline neutrino oscillation experiment using radioactive sources: sterile neutrinos
Atmospheric neutrinos

- Indications of anomaly (80’s)
- Discovery of the neutrino oscillation by SuperK(98)
  - Determination of $\theta_{23}$ & $\Delta M^2_{23}$
  - $\nu_\mu$ oscillation: appearance of $\nu_\tau$
  - Rejection of other explanations
- Current experiment:
  - SuperK
- Main issues now:
  - $\theta_{23}$ octant
  - mass hierarchy
  - CP phase
- Future experiments
  - INO, PINGU, HyperK, …
Looking for sub-leading effects

- Thanks to the huge statistics and large $\theta_{13}$, we can look for:
  - Mass hierarchy: enhanced high energy upward going $\nu_e$ due to the matter effect
  - Octant of oscillation: enhanced low energy $\nu_e$ due to the solar term
  - CP phase $\delta$: interference between these two

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2 \theta_{23} - 1)$$
$$-r \cdot \sin \tilde{\theta}_{13} \cdot \cos^2 \tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos \delta \cdot R_2 - \sin \delta \cdot I_2)$$
$$+2 \sin^2 \tilde{\theta}_{13} \cdot (r \cdot \sin^2 \theta_{23} - 1)$$

Walter@NeuTel’13

Solar term

interference

Matter effect
Recent Super-K results

- Both free and constrained fits prefer 2nd octant
- 1.2σ preference for inverted hierarchy
  sensitivity is 0.9σ
Future experiment: INO

- INO (India-based Neutrino Observatory): 50kt magnetized iron plates interleaved with RPCs: Sign sensitive
- Construction started, operational: 2018
- Sensitivity to mass hierarchy: \(\sim 3\sigma\) after 10 years running

Choubey@neutrino’12
Future experiment: HyperK

- 1 Mt water Cerenkov detector
- 99000 20” PMT, 20% coverage
- Octant issue: $\Delta\sin^2\theta_{23} < 1\%$
- Mass hierarchy: complementary to T2HK
- CP: T2HK much better
Future experiment: PINGU

- A large ice Cerenkov detector with $E_{\text{thresh}} \sim 1$ GeV
- 20 strings with a spacing of 26 m
- Existing IceCube as the VETO
- Equivalent target mass: ~10 Mt
- Sensitivity: ~ 3$\sigma$ in < 2 years (2020)

arXiv:1306.5846
Reactor neutrinos

- Direct detection of neutrinos (50’s)
- Oscillation:
  - Early searches (70’s-90’s):
    - Reines, ILL, Bugey, … Palo Verde, Chooz
  - Determination of $\theta_{12}$ (90’s-00’s):
    - KamLAND
  - Discovery of $\theta_{13}$ (00’s-10’s):
    - Daya Bay, Double Chooz, RENO
- Magnetic moments (90’s-00’s):
  - Texono, MUNU,…
- Mass hierarchy (10’s-20’s):
  - JUNO, RENO-50
- Sterile neutrinos (10’s):
  - Nucifer, Stereo, Solid …

2013-7-23
Latest KamLAND Results: $\theta_{12}$ & $\Delta M_{12}^2$

- Reactors are all off in Japan since Mar. 2011:
  - A unique opportunity for precise measurement of backgrounds

<table>
<thead>
<tr>
<th>Data combination</th>
<th>$\Delta m_{21}^2$</th>
<th>$\tan^2 \theta_{12}$</th>
<th>$\sin^2 \theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND</td>
<td>$7.54^{+0.19}_{-0.18}$</td>
<td>$0.481^{+0.092}_{-0.080}$</td>
<td>$0.010^{+0.033}_{-0.034}$</td>
</tr>
<tr>
<td>KamLAND + solar</td>
<td>$7.53^{+0.19}_{-0.18}$</td>
<td>$0.437^{+0.029}_{-0.026}$</td>
<td>$0.023^{+0.015}_{-0.015}$</td>
</tr>
<tr>
<td>KamLAND + solar + $\theta_{13}$</td>
<td>$7.53^{+0.18}_{-0.18}$</td>
<td>$0.436^{+0.029}_{-0.025}$</td>
<td>$0.023^{+0.002}_{-0.002}$</td>
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</tbody>
</table>

arXiv:1303.4667
### $\theta_{13}$: Three on-going experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Power (GW)</th>
<th>Baseline (m) Near/Far</th>
<th>Detector (t) Near/Far</th>
<th>Overburden (MWE) Near/Far</th>
<th>Designed Sensitivity (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daya Bay</td>
<td>17.4</td>
<td>470/576/1650</td>
<td>40//40/80</td>
<td>250/265/860</td>
<td>~ 0.008</td>
</tr>
<tr>
<td>Double Chooz</td>
<td>8.5</td>
<td>400/1050</td>
<td>8.2/8.2</td>
<td>120/300</td>
<td>~ 0.03</td>
</tr>
<tr>
<td>Reno</td>
<td>16.5</td>
<td>409/1444</td>
<td>16/16</td>
<td>120/450</td>
<td>~ 0.02</td>
</tr>
</tbody>
</table>

**Daya Bay**
- Located near Ling Ao NPP
- Reactors: 4.27 GW x 2 cores
- Baseline: 470/576/1650 m
- Design sensitivity: ~ 0.008

**Double Chooz**
- Near/Far detectors configuration
- Baseline: 400/1050 m
- Design sensitivity: ~ 0.03

**Reno**
- Near/Far detector configuration
- Baseline: 409/1444 m
- Design sensitivity: ~ 0.02
Daya Bay: Data taking & analysis status

- **A** Two Detector Comparison:  
  NIM A 685 (2012), pp. 78-97

- **B** First Oscillation Result:  

- **C** Updated analysis:  
  Chinese Physics C37, 011001 (2013)
Daya Bay: Results(C)

R = 0.944 ± 0.007 (stat) ± 0.003 (syst)

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{(stat)} \pm 0.005 \text{(syst)}$

$\chi^2 / NDF = 3.4/4, \ 7.7 \sigma \text{ for non-zero } \theta_{13}$

F.P. An et al., Chin. Phys. C 37(2013) 011001

Rate+Shape analysis for (D) will be announced at NuFact in Aug. at IHEP
Systematic Errors at Daya Bay: Side-by-Side Comparison

- **Expected ratio of neutrino events:** $R(\text{AD1}/\text{AD2}) = 0.982$
  - The ratio is not 1 because of target mass, baseline, etc.
- **Measured ratio:** $0.987 \pm 0.004(\text{stat}) \pm 0.003(\text{syst})$

This check will determine finally the systematic error

Data set: Dec 24 to May 11
Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency: ~95%)

- **A** (220 days): First $\theta_{13}$ result
  PRL 108, 191802 (2012)

- **B** (403 days): Improved $\theta_{13}$ result
  NuTel 2013

- **C** (~700 days): Shape+rate analysis
  (in progress)

Absolute reactor neutrino flux measurement in progress
[reactor anomaly & sterile neutrinos]

From Soo-Bong Kim
RENO Results

- First result in April 2, 2012.

\[ \sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst}) \]

- A new result reported in March, 2013.

\[ \sin^2 2\theta_{13} = 0.100 \pm 0.010(\text{stat}) \pm 0.015(\text{syst}) \]

\[ R = \frac{\Phi_{\text{Far, observed}}}{\Phi_{\text{Far, expected}}} = 0.929 \pm 0.006(\text{stat}) \pm 0.009(\text{syst}) \]

Statistics:
- about twice more data

Systematics:
- Improved background estimation/reduction (Li/He background, fast N, flasher removal)
- Improved energy scale calibration

For details, see Seon-Hee Seo’s talk at NeuTel’13
Double Chooz: many results

4 measurements → 2 combined (Gd & H) measurements
[preliminary correlations matrix → detector + flux + BG]

remarkable agreement (R+S & RRM) both Gd and H sample → accuracy validation
combined Gd & H individual measurements → higher precision

[DC internal validation cross-checks → (future) compare against Daya Bay & RENO]
\( \sin^2(2\theta_{13}) = (0.109 \pm 0.035) \)

**\( \theta_{13} \) measurement → rate + shape...**

**Gd+H fit... nGd data**
April 2011 – March 2012

- Background-subtracted data
- No oscillation
- Combined best fit: \( \sin^22\theta_{13} = 0.109 \)
  at \( \Delta m^2 = 0.00231 \text{ eV}^2 \)
- Systematic error

**nH data**
April 2011 – March 2012

- Background-subtracted data
- No oscillation
- Combined best fit: \( \sin^22\theta_{13} = 0.109 \)
  at \( \Delta m^2 = 0.00231 \text{ eV}^2 \)
- Systematic error

**Double Chooz Preliminary**

**\( \sin^2(2\theta_{13}) \) measured** via spectral distortion & rate deficit (disappearance) [**only DC**]

- **signal**: includes consistency against oscillation E/L distortion (\( \geq 6 \text{MeV} \) ~irrelevant)
- **BG**: full spectral info for every BG (\( \rightarrow \) what if missing any BG?)
- **detector**: \( \sim 1\% \) precision energy reconstruction [data/MC → non-linearities, etc.]

*Anaetael Cabrera (CNRS-IN2P3 & APC)*
Reactor Rate Modulation (RRM) method

**DC simple site:** 2 powerful reactors
→ 100% flux modulation (→reactor-OFF)

**reactor-OFF:** naked BG (inclusively)

**reactor-ON:** IBDs+BG

**RRM analysis [only DC]**
→ slope[$\sin^2(2\theta_{13})$] & intercept [BG rate]
→ combined Gd+H samples (more precise)

**$\sin^2(2\theta_{13}) = (0.097 \pm 0.035)$**

Anatael Cabrera (CNRS-IN2P3 & APC)
Summary of latest reactor results

- Daya Bay
  - Gd rate: \( \sin^2 2\theta_{13} = 0.089 \pm 0.010^{\text{stat}} \pm 0.005^{\text{syst}} \)

- Double Chooz
  - Rate+Shape: \( \sin^2 (2\theta_{13}) = 0.109 \pm 0.035 \)
  - RRM: \( \sin^2 (2\theta_{13}) = 0.097 \pm 0.035 \)

- RENO
  - Gd rate: \( \sin^2 2\theta_{13} = 0.113 \pm 0.013^{\text{stat}} \pm 0.019^{\text{syst}} \)

- Can we take their weighted average?
  - Yes, if following issues are properly dealt:
    - Correlated errors between experiments
    - Errors are estimated in a unified way

The three experiments will work together to report results in a coherent way, and probably can report a combined result.
Future prospects: Daya Bay

- Calibration & maintenance completed last summer.
- Full detector operational since Oct. 2012
- Precision in 3-5 years: ~4%

We are here now
RENO's Projected Sensitivity of $\theta_{13}$

$$\sin^2 2\theta_{13} = 0.100 \pm 0.010 (\text{stat.}) \pm 0.015 (\text{syst.})$$

- **Goals**
  - $\sin^2 2\theta_{13}$ to 7% precision
  - Direct measurement of $\Delta m^2_{31}$
  - Precise measurement of reactor neutrino flux and spectrum
  - Study for reactor anomaly and sterile neutrinos

From Soo-Bong Kim
Double Chooz

• Near detector in construction till Spring 2014.
• The first result of the full experiment will be available at the end of 2014, towards a final precision of 10%.

From Herve de Kerret
Future Experiment: JUNO

<table>
<thead>
<tr>
<th></th>
<th>Daya Bay</th>
<th>Huizhou</th>
<th>Lufeng</th>
<th>Yangjiang</th>
<th>Taishan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>running</td>
<td>planned</td>
<td>approved</td>
<td>Construction</td>
<td>construction</td>
</tr>
<tr>
<td>power/GW</td>
<td>17.4</td>
<td>17.4</td>
<td>17.4</td>
<td>17.4</td>
<td>18.4</td>
</tr>
</tbody>
</table>

Physics Reach

Thanks to a large $\theta_{13}$

- Mass hierarchy
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- ……

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Daya Bay II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{12}^2$</td>
<td>3%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\Delta m_{23}^2$</td>
<td>5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>5%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>5%</td>
<td>N/A</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>14% $\Rightarrow$ 4%</td>
<td>$\sim$ 15%</td>
</tr>
</tbody>
</table>

Detector size: 20kt
Energy resolution: $3\%/\sqrt{E}$
Thermal power: 36 GW

For 6 years, mass hierarchy can be determined at $4\sigma$ level, if $\Delta m_{\mu\mu}^2$ can be determined at 1% level

Y.F. Li et al., arXiv:1303.6733
Status of JUNO

- Conceptual design & R&D plan approved in China
- Site determined, geological survey will be completed in 2 months
- Detailed civil design underway
- Detector design underway
- R&D started:
  - Detector prototyping
  - LAB-based Liquid scintillators
  - Photo-detectors(PMTs)
  - Readout electronics
- Collaboration will be established by the end of this year
**RENO-50**

- **RENO-50**: An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20” PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant.

**Goals:**
- High-precision measurement of $\theta_{12}$ and $\Delta m_{21}^2$
- Determination of neutrino mass hierarchy
- Study neutrinos from reactors, (the Sun), the Earth, Supernova, and any possible stellar objects

From Soo-Bong Kim
Reactor neutrino anomaly

- By a new flux calculation, there may exist a reactor neutrino flux deficit: $0.943 \pm 0.023$. A $3\sigma$ effect?
- Later confirm by other calculations
- Oscillation with sterile neutrinos?
  - Other experimental “hints”: LSND, MiniBooNE, Gallex…
  - Global fit of all “hints”: severe tensions
  - Cosmological bounds: not so favored
- New analysis: less severe the effect?

T.A. Mueller et al., PRC83:054615,2011
P. Huber et al., PRC84:024617,2011.
C. Zhang et al., arXiv: 1303.0900
Solution: experiments

- **Radioactive sources:** CeLAND\(^{144}\text{Ce}\) in KamLAND, SoX\(^{51}\text{Cr}\) in Borexino, ...
- **Accelerator beams:** IsoDAR, Icarus/Nessie, nuSTORM...
- **Reactors:** Nucifer, Stereo, Solid, SCARR, ...
  - Backgrounds near by reactors
  - Precision better than 1%
- **New measurements of \(\beta\)-spectrum from U & Pu(Munich)**

**Nucifer**

Figures from T. Lasserre

Will be upgraded to reduce backgrounds
Summary

• Solar neutrinos continue to provide improved measurements of $\theta_{12}$ & $\Delta M^2_{12}$; solar-related and other astrophysics issues require much larger detectors.

• Atmospheric neutrinos can improve the precision of $\theta_{23}$ & $\Delta M^2_{23}$; sub-leading effects can be used to determine the mass hierarchy & CP phase.

• Reactor neutrinos provided precise measurements of $\theta_{13}$ & $\Delta M^2_{13}$; next generation experiments can measure precisely $\theta_{12}$ & $\Delta M^2_{12}$ & $\Delta M^2_{23}$, determine the mass hierarchy, and study many astrophysics issues.

• Sterile neutrino issues will be settled by experiments at reactors and/or using radioactive sources & accelerators, sooner or later.

Mass hierarchy and CP phase will be known in a not too far future.