Perspectives on neutrino physics

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Oscillations

\[ P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(L) \rangle|^2 \]

\[ = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2[1.27\Delta m_{ij}^2 L / E] \]

\[ + 2 \sum_{i>j} \Im(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin[2.54\Delta m_{ij}^2 L / E] \]

- **Neutrino flavor oscillations** – access to \( U_{\text{PMNS}} \) and \( \nu \) mass-squared splittings
- In past decade, **phenomenon confirmed** and the **texture of \( \nu \) mixing** extracted:
  - Experiments using **solar, atmospheric, reactor, and accelerator \( \nu \) sources**

Sun, imaged with \( \nu \)

Cosmic rays

Daya Bay NPP

Fermilab
**“Solar” parameters $\theta_{12}$ and $\Delta m^2_{21}$**

- **SNO** (solar), **Super-K** (solar), **KamLAND** (reactor)
- No big change expected from current experiments (Future reactor expts. [e.g. JUNO] in the works)

**Measured solar $\nu$ fluxes**

**KamLAND $L/E$ oscillation signature**

\[ \Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2 \] (2.4%)

\[ \sin^2 \theta_{12} = 0.304^{+0.014}_{-0.013} \] (4.4%)
"Atmospheric" parameters $\theta_{23}$ and $|\Delta m_{32}^2|$

- Super-K (atmos.), MINOS (accel.), T2K (accel.), NOvA (accel.), Daya Bay (reactor), IceCube (atmos.), and others
- Measurements still rolling in…

$$\Delta m_{32}^2 = (2.42 \pm 0.06) \times 10^{-3} \text{ eV}^2 \quad (3\% \text{ for NH})$$

$$\sin^2 \theta_{23} = 0.514^{+0.055}_{-0.056} \quad (11\% \text{ for NH})$$
\( \theta_{13} \) from reactor measurements

**Daya Bay**: \( \sin^2 \theta_{13} = 0.021 \pm 0.001 \) \( 5\% \)

8 detectors in total, rate+shape signal extraction, combined nGd and nH results (new).
Also a 4\% measurement of \( \Delta m_{ee}^2 \). Will run until 2017.

**Double Chooz, RENO are compatible**

*Higher central values, but errors still relatively large*

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PRL 115, 111802 (2015)

**Daya Bay**

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Neutrinos have mass

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen’s University, Kingston, Canada

FUNDAMENTAL PHYSICS BREAKTHROUGH PRIZE

Kam-Biu Luk and the Daya Bay Collaboration

Yifang Wang and the Daya Bay Collaboration

Koichiro Nishikawa and the K2K and T2K Collaboration

Atsuto Suzuki and the KamLAND Collaboration

Arthur B. McDonald and the SNO Collaboration

Takaaki Kajita and the Super K Collaboration

Yoichiro Suzuki and the Super K Collaboration
Questions

| \[ |U_{\mu 3}| = |U_{\tau 3}|?\]
| “maximal mixing” |

- Are neutrinos \textbf{Majorana} or \textbf{Dirac} fermions?
- GUT-scale physics? (see-saw connection)
- Absolute masses?

- Light sterile states? (experimental anomalies)
- Mass ordering? (“hierarchy”)
- Unitary?
- Leptonic CP violation?

- \[U_{\text{PMNS}}\] highly off-diagonal, in contrast with \[U_{\text{CKM}}\]
  (model building, unification, new physics, ...)

\[quark\ \text{mixing:}\]

- \(\nu_e\), \(\nu_\mu\), \(\nu_\tau\)

\text{astrophysics/cosmology (solar }\nu,\text{ supernovae, ultra-high-energy }\nu,\text{ CvB)}

\text{...and more (geoneutrinos, nuclear processes, }\nu\text{ interactions)}

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Theoretical answers?

“If you measure it, they will come.”

As experimental info grows, the need (and ability) to explain specific observed textures grows with it.

words in recent abstracts

Number of theory papers each year with something to say about the structure of $\nu$ mixing and masses

(using an admittedly crude search)
\[ \theta_{13} > 0 \Rightarrow \text{LBL } \nu_\mu \rightarrow \nu_e \]

Makes feasible \textbf{long-baseline measurements} of…

**neutrino mass hierarchy**
via matter effects that modify \( P(\nu_\mu \rightarrow \nu_e) \)

*Implications for:* \( 0\nu\beta\beta \) data and Majorana nature of \( \nu \); approach to \( m_\beta \);
astrophysics; theoretical frameworks for mass generation, quark/lepton unification;
Is the lightest charged lepton associated with the heaviest light neutrino?

**CP violation**
via dependence of \( P(\nu_\mu \rightarrow \nu_e) \) on \( CP \) phase \( \delta \). Amplified by \( \nu/\bar{\nu} \) comparisons.
baryon asymmetry through see-saw/leptogenesis; fundamental question in the Standard Model (is \( CP \) respected by leptons?)

**\( \nu_3 \) flavor mixing**
via leading-order factor \( \sin^2(\theta_{23}) \)
Is \( \nu_3 \) more strongly coupled to \( \mu \) or \( \tau \) flavor?;
fundamental frameworks for mass generation, unification
Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch...

**At right:**

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$ plotted for a single neutrino energy and baseline

For fixed $L/E = 0.4$ km/MeV

NOvA
(810 km)

$|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV$^2$

$\sin^2(2\theta_{23}) = 1$

$\sin^2(2\theta_{13}) = 0.09$
Long-baseline $\nu_\mu \rightarrow \nu_e$

A more quantitative sketch...

**At right:**

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \; \text{vs.} \; P(\nu_\mu \rightarrow \nu_e)$$

plotted for a single neutrino energy and baseline

Measure these probabilities

*(an example measurement of each shown)*

Also:

Both probabilities $\propto \sin^2 \theta_{23}$
- Tokai to Kamioka (295 km)
- Neutrino beam from J-PARC
- Storied far detector: *Super-K*
- INGRID and ND280 near detectors
- 2014: First definite observation (7.3\(\sigma\)) of \(\nu_\mu \to \nu_e\) appearance
  - NH, \(\delta=3\pi/2\) is best fit, but only slightly so
- 10% of planned data set
- “Short” 295-km baseline:
  - Important role in global \(\nu\) fits (minimal hierarchy dependence)
- Also, \(\bar{\nu}_\mu \to \bar{\nu}_e\) appearance search, with 10% of planned exposure
- 3 events observed, consistent with any oscillation parameters (or no appearance at all; bkgnd \(\approx 1.6\) events)
  - Best fit is again at NH, \(\delta=3\pi/2\), but only (very) slightly so
- Fermilab to Ash River, MN
- Upgraded NuMI beam
- 810 km baseline introduces significant matter effects ⇒ mass hierarchy sensitivity
- Functionally identical near and far detectors
- Full operations began 2014
- **2015:** $\nu_\mu \rightarrow \nu_e$ appearance result with small data set (7.6% of nominal exposure)

- Two complementary event selectors saw 6 and 11 events → on the high end of expectations

- **NH, $\delta$ near $3\pi/2$** is best fit, but only slightly so
- IH disfavored at $>2.2\sigma$ for all $\delta$ by one of the selectors (careful: look elsewhere effect)
- New NOvA results expected this summer with twice the exposure
NOvA + T2K reach with planned exposures

- Many such studies. Shown here is: K. Abe et al. (T2K), Prog. Theor. Exp. Phys. 043C01 (2015)

- Current best fit point of NH, \( \delta \approx 3\pi/2 \) is best case:
  - hierarchy determination at 3.3\( \sigma \) (3.1\( \sigma \) from NOvA)
  - \( \sin(\delta) \neq 0 \) observation at 2.4\( \sigma \)

- Can still be anywhere on the map, though.

Will the planned exposures happen?

- **NOvA:** likely yes
  550 kW → 700 kW possible by end of year. May involve running past 6-yr mark.

- **T2K:** can happen after investment
  350 kW → 750 kW requires Main Ring upgrades (approved!) and/or increase in accelerator livetime.
DUNE

• Next generation LBL experiment
  Plus: supernova neutrinos, nucleon decay, atmospheric neutrinos, and near-det physics)

• 1300 km neutrino baseline
  No parameter degeneracies can remain

• DUNE has significant support in the agencies, laboratories, and international community. Movement to CD-3a later this year.

• Full-scale component prototypes to operate at CERN over next few years. Smaller scale prototypes operating now (e.g., 35-ton at FNAL)
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  operating now (e.g., 35-ton at FNAL)
  
  First 20 kton + beam, c. 2026
• CPv at 3σ for 65% of δ range; >5σ at peak (beam data only)
• Definitive hierarchy measurement
Hyper-K

- A bigger Super-K / T2K
  - 560 kton fiducial mass
  - Goals qualitatively similar to DUNE
    (different emphasis on atmospheric and solar $\nu$; different $p$-decay channels)
  - Still gathering momentum …

JUNO

- A bigger, better KamLAND (via Daya Bay)
  - Precision PMNS
  - (Possible) $3-4\sigma$ on $\nu$MH before 2030
  - Construction has begun, concurrent with detector R&D

<table>
<thead>
<tr>
<th>KamLAND</th>
<th>JUNO</th>
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<tbody>
<tr>
<td>$\sim 1$ kton</td>
<td>20 kton</td>
</tr>
<tr>
<td>$\sim 34%$</td>
<td>$\sim 80%$</td>
</tr>
<tr>
<td>$\sim 6%/\sqrt{E}$</td>
<td>$\sim 3%/\sqrt{E}$</td>
</tr>
<tr>
<td>$\sim 250$ p.e. / MeV</td>
<td>$\sim 1200$ p.e. / MeV</td>
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Similarly, RENO: still gathering momentum, support
So, neutrinos have mass

• And this mass is **rather small**

• What are we dealing with?
  
  - Neutrinos are Majorana fermions and are pointing to new physics  
    *(seesaw mechanism, new states at high mass scale)*
  
  - Neutrinos are just another Dirac fermion, but they couple to the Higgs very weakly?  
    \( m_\nu / m_{EW} < 10^{-12} \)
  
  - Neutrinos couple to a different Higgs sector?
  
  - Other?

• Oscillation experiments continue **looking for failures** of standard assumptions (>3 \( \nu \), non-unitary PMNS, NSI, effective CPTv)

• But to **get at neutrino mass** directly…
• Cosmological observations \(\rightarrow\) sum of neutrino masses.

\[ \text{Best limits: } \Sigma m_i < 0.23 \text{ eV } (95\% \text{ C.L.}) \]

Planck collaboration, arXiv:1502.01589

• \(\beta\)-decay kinematic measurement \(\rightarrow\) effective \(\nu_e\) mass, a.k.a. \(m_\beta\):

\[ m^2_\beta = \sum |U_{ei}|^2 m^2_i \]

• \(0\nu\beta\beta\) decay process (if Majorana-\(\nu\)-mediated) \(\rightarrow\) effective mass \(m_{\beta\beta}\):

\[ m^2_{\beta\beta} = \left| \sum U^2_{ei} m_i \right|^2 \]

\[ n \xrightarrow{\text{kinematic measurement}} p \]

\[ 0\nu\beta\beta \]

\[ n \xrightarrow{\nu} p + e^- \]

\[ n \xrightarrow{\nu} p + e^- \]

\[ m(\nu_e) = 0 \text{ eV} \]

\[ m(\nu_e) = 1 \text{ eV} \]

\[ \text{region close to endpoint} \]

\[ \text{entire spectrum} \]

\[ \text{only } 2 \times 10^{-13} \text{ of decays in last } 1 \text{ eV interval} \]
KATRIN

- Only current kinematic $\nu$ mass experiment
  (several others in R&D phases)
- Large electrostatic filter for $\beta$ spectrometry
- Tritium running expected in 2016

$5\sigma$ reach for $m_\beta = 0.35$ eV
One recent R&D result of note…

- **Project 8**: measure cyclotron frequency of single electrons
- **Entirely new spectroscopic technique** → *very different path to* $m_\beta$
- **Compatible (in principle) with atomic tritium source** → *pass IH mass range*

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**Project 8 collaboration, PRL 114, 162501 (2015)**

- *single electron emitting cyclotron radiation*
- and a spectrum of them…

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Many experiments (~10) techniques isotopes

Example 0νββ signature


EXO-200

CUORE

NEMO

KamLAND-Zen

Chimney
Corrugated Tube
Film Pipe
Suspending Film Strap
Photomultiplier Tube

Buffer Oil
Outer Balloon (13 m diameter)
Inner Balloon (3.08 m diameter)

Xe-LS 13 ton (300 kg $^{136}$Xe)

Outer LS 1 kton

3 m

4 m

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Recent results from
**EXO-200** (¹³⁶Xe),
**KamLAND-Zen** (¹³⁶Xe),
**GERDA** (⁷⁶Ge)
**CUORE** (¹³⁰Te)
→ no signal so far

Nuclear matrix element calculations lead to large uncertainties in $m_{\beta\beta}$

Current generation of expts.
(7 – 200 kg of $\beta\beta$ isotope; results through rest of decade)

- Pushing through IH will require next generation of expts, aiming for $m_{\beta\beta}\sim0.01$ eV

Though, R&D leaps in current generation are still possible
(e.g. enhanced $^{130}$Te loading in SNO+)

Conclusion of November 2015 NSAC Report on $0\nu\beta\beta$:
Let current activities play out for a few more years to make a better informed down-select decision for ton-scale experiments.
LSND, MiniBooNE, reactor, $^{71}$Ga anomalies

• What’s going on?
  - Sterile neutrinos?  *(Need multiple sterile states to accommodate all of today’s data.)*
  - Something else new?
  - A series of systematics issues?

• Many null results in past decade+ *(KARMEN, Bugey, Super-K, MINOS, ICARUS, IceCube, Planck)*, but situation lingers

**Past reactor data: 6% deficit relative to expectation**

**Future experiment(s) need a viable path toward...**

...large exposures
...minimized systematic errors
...in-detector L, E signatures
...unambiguous sensitivity

Attempts that stop short of this will only make things murkier.
Reactor flux uncertainties already known to be **underestimated**?

4 – 6 MeV excess seen in all three recent reactor flux measurements

Many efforts represented, at various stages of development

$10M earmarked for a handful of these.  (Review process complete. Funding decisions to come soon)

Areas most represented:
- neutrino anomalies
- detector R&D
- cross sections (incl. CEνNS)
- $m_\beta$, $m_{\beta\beta}$
Fermilab SBN program

- **Funded outside** the $10M INP budget
- **MicroBooNE + ICARUS + new SBND**
- A mix of **R&D and physics** goals

*Sensitivity shown below has caveats...*
Summary

- Active *experimental* and *theoretical* playing field
- **Mass hierarchy:** *Actionable info soon?*
- **Leptonic CPv:** *Primary goal of next generation LBL expts. (Hints by 2020?)*
- **Majorana vs. Dirac:** *When/if we can answer depends on the answer*
- **What’s up with all the anomalies?**
- **ν scattering:** *Not discussed here; role could be large in the future; plus, new ground being broken (meson exchange currents, CEνNS)*
- **New physics lurking in neutrino sector?** *Minimal theoretical guidance; keep pushing precision and looking for chinks in the armor*