A SNAPSHOT OF EXPERIMENTAL NEUTRINO PHYSICS

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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

“for the discovery of neutrino oscillations, which shows that neutrinos have mass”

In what follows I will follow developments related to the study of neutrino mass
Neutrino mass and mixing

- Neutrino come in three “flavor” eigenstates \((\nu_e, \nu_\mu, \nu_\tau)\)
- Likewise, neutrinos come in three mass eigenstates \((\nu_1, \nu_2, \nu_3)\)
- The mass and flavor eigenstates “mix” (summarized in unitary matrix \(U\))
  - Neutrinos are produced in flavor eigenstates by weak interaction
  - Mass eigenstates evolve differently in proper time \((L/E)\).
  - New flavor components appear \(\rightarrow\) “neutrino oscillations”

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**Amplitudes:** mixing matrix \(U\)

**Wavelength** in \(L/E\): mass\(^2\) splittings.

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} \quad \text{in vacuo}
\]

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

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

- \(\Delta m^2_{ij} (\text{eV}^2)\)
- \(L\) (km)
- \(E\) (GeV)

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**\(P(\nu_e \rightarrow \nu_e)\) vs. \(L/E\),**

Data - BG - Geo \(\nu_e\)

- Expectation based on osci. parameters determined by KamLAND

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**Diagram:**

- E, \(\mu\), \(\tau\)
- Mass eigenstates: \(|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle\)
- Neutrinos: \(\nu_e, \nu_\mu, \nu_\tau\)
- Mass splittings:

\[
\Delta m^2_{ij}(L/E) = \Delta m^2_{ij} + \frac{1}{2} \Delta m^2_{01}(L/E) \quad \text{for} \quad i = 1
\]

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**Equation (13):**

\[
\frac{P(\nu_e \rightarrow \nu_e)}{P(\nu_e \rightarrow \nu_e)_{\text{in vacuo}}} = \frac{|\langle \nu_e | U_{\alpha i} | \nu_i \rangle|^2}{|\delta_{\alpha\beta}|^2}
\]

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**Note:** Sophisticated treatments continue to yield new insights [4]. Somewhat subtle. To do justice to the physics requires a more refined treatment [3] than approximately.

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**Figure:**

- Survival probability
- \(P(\nu_e \rightarrow \nu_e)\)
- L/E vs. \(L/E\)
- Data - BG - Geo
- KamLAND

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**Reference:**

- Neutrino oscillations
- Mass eigenstates
- Mass splittings
- Neutrino production by weak interaction
- Proper time evolution
- New flavor components

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**Additional Information:**

- Neutrino mass and mixing
- Neutrino properties
- Neutrino oscillations
- Neutrino production
- Neutrino evolution

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**Legend:**

- Data - BG - Geo
- KamLAND
- Survival probability
- Neutrino oscillations
- Mass eigenstates
- Mass splittings
- Neutrino production by weak interaction
- Proper time evolution
- New flavor components

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**Conclusion:**

- Neutrino mixing
- Neutrino oscillations
- Mass eigenstates
- Mass splittings
- Neutrino production by weak interaction
- Proper time evolution
- New flavor components
When a neutrino mass is the same way that this model accommodates quark and charged lepton masses, it is straightforward to extend the SM to accommodate these physics that give them mass.

Whether neutrinos may be their own antiparticles depends on the nature of the IV. The neutrino-anti-neutrino relation:

- Three rotation angles ($\theta_{12}, \theta_{13}, \theta_{23}$)
- One complex phase $\delta_{\text{CP}}$

- additional phases possible if neutrinos are “Majorana”
- changes sign for antineutrino oscillations (“CP odd”)

$$\nu_i = U_{ei}^* \nu_e + U_{\mu i}^* \nu_\mu + U_{\tau i}^* \nu_\tau$$

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

- Neutrino oscillations in atmospheric neutrinos:
  - mass$^2$ splitting of $\sim 2.5 \times 10^{-3} \text{ eV}^2 (\Delta m^2_{\text{atm}} \sim \Delta m^2_{21}, \Delta m^2_{32})$
  - first maximum at 500 km/GeV
- Solar neutrinos, reactor:
  - mass$^2$ splitting of $\sim 7.8 \times 10^{-5} \text{ eV}^2 (\Delta m^2_{\text{sol}} = \Delta m^2_{21})$
DIRECT MASS MEASUREMENTS

Adapted from S. Mertens @ NEUTRINO 2020

\[ m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2 \]

- Detect turnover at kinematic endpoint of $^3$H $\beta$ decay due to $m_\nu > 0$
- Challenge: only $10^{-13}$ of decays would occur in relevant region
  - need an intense source: $\sim 10^{11}$ decays/sec
  - need excellent energy resolution: $\sim 1$ eV
**KATRIN RESULTS**

**Effective 5 days of data**
- Stat. error: ± 2
- Syst. error: ± 6

- $m^2 = (-1.0^{+0.0}_{-1.1})$ eV$^2$ (16% probability for $m_\nu = 0$)
- $m_\nu < 0.8$ eV (FC CL), 0.9 eV (Bayes CI) at 90%
PROSPECTS

KATRIN:

- First results are with
  - 22 days operation, 22% gas density, $2.45 \times 10^{10}$ Bq source strength
- Analysis of data from 2nd campaign soon:
  - 31 days operations, 84% gas density, $9.8 \times 10^{10}$ Bq source strength
  - 3rd campaign started with improved experimental conditions

- Cyclotron radiation from $\beta$ electrons orbiting in magnetic field:
  - PROJECT 8

- Electron capture in Holomium:
  - Holmes, ECHO

Cyclotron radiation from $\beta$ electrons orbiting in magnetic field:

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Electron capture in Holomium:

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THE NATURE OF NEUTRINO MASS

\[ 0\nu\beta\beta \]

- Neutrinos are unique among fermions in the possibility of being Majorana fermions
  - a right handed field is needed to give neutrinos mass
  - the neutrino, antineutrino may come together to create the neutrino mass term
- This can mediate the “neutrino less double beta decay process” in certain nuclei
  - two neutrons undergo simultaneous b decay, without neutrino emission
  - the total energy of the electrons is at the endpoint of the double b decay spectrum
- Observation of this process would indicate neutrinos are Majorana particles

adapted from J. Detwiler @ Neutrino 2020
A large number of detection technologies are in play with different optimizations of:

- 0ν2β isotope (Q, isotopic abundance)
- energy resolution
- event characterization, background rejection
- scalability

Leading experiments achieve T_{1/2} limits of:

- $^{136}$Xe: $> 10^{26}$ yrs
- $^{76}$Ge: $> 10^{26}$ yrs
- $^{130}$Te: $> 3 \times 10^{25}$ yrs
• Experiments are reaching sensitivities approaching the 0ν2β rate expected for inverted mass ordering ($m_{\beta\beta} \sim 50$ meV)
• The next generation of experiments aim to fully cover 0ν2β rates expected from inverted mass ordering ($m_{\beta\beta} \sim 10$ meV)
\[ P(\nu_e \to \nu_e) \sim 1 - \sin^2 2\theta_{13} \sin^2 (1.27\Delta m^2_{31}/E) - \sin^2 2\theta_{12} \sin^2 (1.27\Delta m^2_{21}/E) \]

- Liquid scintillator: detecting reactor $\bar{\nu}_e$ since the discovery of (anti)neutrinos through IBD
- Detectors ~2 km from reactor precisely measure $\theta_{13}, \Delta m^2$
  - Daya Bay, Double CHOOZ, RENO
  - $\sin^2 \theta_{13} = 0.0218 \pm 0.0007$ (PDG 2019)
  - $\Delta m^2_{ee} = (2.52 \pm 0.07) \times 10^{-3} \text{eV}^2$ (DB)

**JUNO:**
- 20 kt detector at 60 km to analyze “beating” of oscillations sensitive to mass ordering
- scheduled for completion in 2021 with data taking in 2022!
To first order, accelerator-based neutrino beams operate on the same basic principles:

1. High energy protons impinge on a target
   - pions are produced
2. Electromagnets focus pions into a decay region
   - one sign is focussed, the other defocussed
3. The pions decay in a decay pipe
   - muon (anti)neutrinos are produced
4. Beam absorber stops all other remaining particles
   - some muons penetrate and can be monitored.
   - neutrinos go on to the experiment

Each step represents an enormous technical challenge:

- Primary proton beams approaching 1 MW in power
- Hundreds of kA of current to focus the beam

**Currency: “protons-on-target”**

n.b. Non-trivial exchange rate when comparing different beams
**LONG BASELINE EXPERIMENTS**

Accelerator-based beams are typically $E_\nu \sim \text{few GeV}$

- “on-axis” beams provide the highest rate, width of spectrum
- “off-axis” beams to maximize the oscillation probability, reduce background

Maximize oscillations for $\Delta m^2_{\text{atm}} \rightarrow 500 \text{ km/GeV}$

\[
P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 (1.27 \Delta m^2_{31} L/E)
\]

\[
P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}
\]

\[
\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \quad \Delta \equiv \frac{\Delta m^2_{31} L}{4E}
\]

- $\theta_{23}$ (as opposed to $2\theta_{23}$) dependence $\rightarrow$ “octant” dependence if $\theta_{23} \neq 45^\circ$
- CP odd phase $\delta_{\text{CP}}$: asymmetry of oscillation probabilities: $P_{\text{VAC}}(\nu_\mu \rightarrow \nu_e) \neq P_{\text{VAC}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Mass ordering sensitivity through $x$: $\nu_e(\bar{\nu}_e)$ enhanced in normal(inverted) hierarchy
**EXPERIMENTS**

Super Kamiokande

"far" detector

$E_\nu = 0.6$ GeV $\nu_\mu/\bar{\nu}_\mu$ beam

L = 295 km

$E_\nu = 2$ GeV $\nu_\mu/\bar{\nu}_\mu$ beam

L = 810 km

$\nu_\mu$ CC @ NOvA

$\nu_e$ CC @ NOvA

Fermilab

L = 295 km

L = 810 km
\[ P(\nu_\mu (\bar{\nu}_\mu) \rightarrow \nu_e (\bar{\nu}_e)) \] AT T2K AND NOvA

- Left: At 0.6 GeV, ~300 km, matter effects at T2K are relatively small

\[ x = \pm \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2_{31}} \]

- Right: At 2 GeV, ~800 km, matter effects at NOvA are larger
\( \nu_\mu/\bar{\nu}_\mu \) EVENTS AT FAR DETECTOR

\[
P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (\cos^4 \theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2(1.27\Delta m_{31}^2 L/E)
\]

Both experiments see large disappearance for both \( \nu_\mu \) and \( \bar{\nu}_\mu \).

Disappearance is consistent with “maximal” oscillation with \( \theta_{23} \sim \pi/4 \).
Both experiments definitively see $\nu_\mu \rightarrow \nu_e$.

NOvA also has clear indications of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$. 

$\nu_e/\bar{\nu}_e$ EVENTS AT FAR DETECTOR
• T2K and NOvA measurements are compatible in $\theta_{23}$ and $\Delta m^2_{32}$

• Some tension in $\delta_{CP}$:
  • T2K: large $\nu_e$, small $\nu_e$ appearance (NH, $\delta_{CP}\sim-\pi/2$)
  • NOvA: large $\nu_e$, $\nu_e$ appearance
• 1.2 MW beam from FNAL to SURF (1300 km)
• 4 x 10 kT Liquid Argon Time Projection detectors
  • See more from D. Caratelli
• Broad beam, higher energy, longer baseline
  • very powerful capability to resolve mass ordering
  • broad beam to probe additional oscillation maxima
HYPER-KAMIOKANDE

- Super-Kamiokande → Hyper-Kamiokande
- ~22.5 kt → 188 kt
- Detector in Korea (KNO) at ~1100 km would also be sensitive to 2nd oscillation maximum

Recently advanced by MEXT for funding by Ministry of Finance
IceCube “low energy” program is probing atmospheric neutrino parameters

- Projected competitive measurements in $\theta_{23}$ and $\Delta m_{32}^2$
- Unique high statistics $\nu_\tau$ appearance measurements
BEYOND THE NEXT GENERATION

• **INO**: 51 kT **magnetized** iron calorimeter using resistive plate chambers to study atmospheric neutrinos

• **THEIA**: 100 kT **hybrid** Water Cherenkov/Scintillation detector

• **ESSvB**: ~0.3 GeV neutrino beam produced using **5 MW** ESS 3 GeV proton source to study 2nd oscillation maximum

adapted from J. Klein @ Neutrino 2020
A number of anomalies are attributed to neutrino oscillations:

- Deficits of \( \bar{\nu}_e \) (from reactors), appearance of \( \nu_e \)-like events in \( \nu_\mu \) beams
- "short" baselines = fast oscillations
  - imply mass splittings \( O(1 \, \text{eV}^2) \) inconsistent with the standard three neutrino flavor framework
- Such oscillation may be driven by "sterile" neutrino mass states mixing with the active flavors

This is a complicated picture:

- The anomalies are not consistent
- Cannot rule out that some of the anomalies have nothing to do with neutrino oscillations (or even neutrinos)

Resolution of these anomalies is very important!
• FNAL Short Baseline Neutrino (SBN) program probing $\nu_\mu \rightarrow \nu_x$ oscillations with $\Delta m^2 \sim \mathcal{O}(1 \text{ eV}^2)$
  • 3 LArTPCs on the Booster Neutrino Beam with $\sim 0.8 \text{ GeV} \nu_\mu$ beam
    • 110 m (SBND), 470 m ($\mu$BooNE), 600 m (ICARUS)
    • Important ability to discriminate $e/\gamma$ from neutrino interaction
    • Results expected from $\mu$BooNE soon
    • Ongoing commissioning of ICARUS detector!
• JSNS2: stopped $\pi^+$ beam at J-PARC to search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
  • Reproduce LSND signature with $\bar{\nu}_e + p \rightarrow e^+ + n$ signature
  • Started operations!
• Reactor experiments:
  • DANSS, NEOS, PROSPECT, SoLid, etc.
MYSTERIES:

- Unexplained physics in the Standard Model . .
- Whence mixing and mass parameters?
- Do neutrinos have a different origin?

\[
|U_{QUARK}| \sim \begin{pmatrix}
0.97428 & 0.2253 & 0.0034 \\
0.2252 & 0.93745 & 0.0410 \\
0.00862 & 0.0403 & 0.99915
\end{pmatrix}
\]

\[
|U_{LEPTON}| \sim \begin{pmatrix}
0.8 & 0.5 & 0.15 \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

Mass (eV)

- \(10^9\)
- \(10^6\)
- \(10^3\)
- \(10^0\)
- \(10^{-3}\)
CONCLUSIONS

• It’s a golden age for neutrino experiments
  • it’s been a “golden age” for neutrinos for a while . . .
  • Answers to old questions → fascinating new ones

• Current experiments may be hinting towards an “interesting” answer:
  • Neutrino masses are tiny!
  • They may be a Majorana particle!
  • One neutrino mixing parameter near theoretically maximal value!
  • CP violating phase may be large, possibly maximal . . . .!
  • There may be anomalies that point to exciting new physics!

• If this is the answer, what was the question?
  • What determines the value of neutrino mixing parameters and masses?
  • What role does the neutrino play in shaping our universe?

• The golden age continues with new experiments and opportunities