Towards new discoveries with neutrinos (and dark matter)

RICHARD HILL

TRIUMF
Perimeter Institute
U. Chicago

2016 CAP Congress, University of Ottawa

14 June, 2016
Outline

• the discovery of neutrino mass

• open questions

• experimental probes: neutrinoless double beta decay and long baseline neutrino oscillation

• theoretical challenges

• summary
• neutrino mass is physics beyond the standard model

  • fermion mass terms in quantum field theory are constrained by gauge invariance

  • in the renormalizable standard model, there is no mass term for the neutrino
Theory was critical to establishing the solar neutrino puzzle.

Flux of $\nu_e$ produced in Sun > flux of $\nu_e$ surviving at Earth

\[ p \rightarrow \nu_e n e^+ \]

\[ \nu_e n \rightarrow p e^- \]

Standard solar model flux:

\[ \phi_{SSM} = 5.05^{+1.01}_{-0.81} \times 10^6 \text{cm}^{-2}\text{s}^{-1} \]

\[ \phi_{observed} \sim \frac{1}{3} \text{ of this} \]
Experiment establishes neutrino flavor conversion

charged current (CC):

$$\nu_e d \rightarrow p p e^-$$

neutral current (NC):

$$\nu_{e,\mu,\tau} d \rightarrow p n \nu_{e,\mu,\tau}$$

elastic scattering

$$\nu_{e,\mu,\tau} e^- \rightarrow \nu_{e,\mu,\tau} e^-$$

A. McDonald
Nobel prize 2015
Experiment establishes neutrino flavor conversion

charged current (CC):

$$\nu_e d \rightarrow p p e^-$$

neutral current (NC):

$$\nu_{e,\mu,\tau} d \rightarrow p n \nu_{e,\mu,\tau}$$

elastic scattering

$$\nu_{e,\mu,\tau} e^- \rightarrow \nu_{e,\mu,\tau} e^-$$

confirms $\nu_e$ deficit

A. McDonald
Nobel prize 2015
Experiment establishes neutrino flavor conversion

charged current (CC):

$$\nu_e d \rightarrow pp e^-$$

neutral current (NC):

$$\nu_{e,\mu,\tau} d \rightarrow pn \nu_{e,\mu,\tau}$$

elastic scattering

$$\nu_{e,\mu,\tau} e^- \rightarrow \nu_{e,\mu,\tau} e^-$$

establishes neutrino flavor transformation

confirms $\nu_e$ deficit

A. McDonald
Nobel prize 2015
Theory and experiment established atmospheric neutrino oscillation

flux of $\nu_\mu$ produced in atmosphere $> \quad$ flux of $\nu_\mu$ surviving at Earth

@ Neutrino 1998 conference

T. Kajita
Nobel prize 2015
Theory and experiment established atmospheric neutrino oscillation

flux of $\nu_\mu$ produced in atmosphere $>$ flux of $\nu_\mu$ surviving at Earth

@ Neutrino 1998 conference
Flavor transformation is a manifestation of neutrino mass

\[ H = \sum_i \sqrt{m_i^2 + p^2} |\nu_i\rangle \langle \nu_i| \]

charge eigenstates

mass eigenstates

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

\[ P(\nu_\ell \to \nu_{\ell'}) = \delta_{\ell\ell'} - 4 \sum_{i>j} R(U_{\ell i}^* U_{\ell' i} U_{\ell j} U_{\ell' j}^*) \sin^2 \left[ 1.27 \Delta m_{ij}^2 (\text{eV}^2) \frac{L(\text{km})}{E(\text{GeV})} \right] 
\]

\[ \pm 2 \sum_{i>j} I(U_{\ell i}^* U_{\ell' i} U_{\ell j} U_{\ell' j}^*) \sin^2 \left[ 2.54 \Delta m_{ij}^2 (\text{eV}^2) \frac{L(\text{km})}{E(\text{GeV})} \right] 
\]

when one mass splitting is relevant:

\[ P(\nu \to \nu') = \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (\text{eV}^2) \frac{L(\text{km})}{E(\text{GeV})} \right] \]
Manmade neutrino sources have confirmed the basic picture

![Graph showing expected and observed reactor anti-neutrino spectra](image)

and established the magnitude of mixing between three different flavors

![Graph showing Far hall and Near halls (weighted) entries](image)
• historical recap

• neutrino transformation firmly established

• important interplay between theory and experiment

  - **theory**: predicts flux in absence of oscillation (solar, atmospheric, reactor)

  - **experiment**: observes flux different from prediction

  theory enters again, providing interaction cross sections to translate event rate to flux

• same interplay for current and next generation experiments exploring this physics beyond the standard model
• modern theory framework

Having established neutrino mass, revisit the assumptions that caused us to predict its absence

1) renormalizability
   
in modern understanding, renormalizability is a strange concept ( = infinite cutoff energy )

2) absence of “sterile” neutrinos

Violating either of these amounts to physics beyond the standard model. For (1), and in general also for (2), find lepton number violation

A lot of unanswered questions…
• unresolved questions for neutrinos

#1 is lepton number really violated?

The unique first order perturbation to the Standard Model:

\[
\mathcal{L} = \frac{1}{\Lambda} LLHH
\]

- Majorana mass term for neutrino
- Lepton number violating
- Nonrenormalizable, mass scale $\Lambda \sim 10^{16}$ GeV (!!!)
unresolved questions for neutrinos

#2 how are neutrino masses arranged: are they about equal, or hierarchical, and in what order?

• determines observability of lepton number violation, #1
• unresolved questions for neutrinos

#3 how many sterile neutrinos are there?

• with 3, can form lepton-number conserving mass terms for 3 neutrino states

• with more than 3, find new mass splitting and oscillation lengths

• some intriguing hints, and new experimental probes
unresolved questions for neutrinos

#4 is CP symmetry violated?

- do neutrinos behave differently from anti-neutrinos?

- CP violation a necessary ingredient to generate the baryon asymmetry of the universe.

- known sources of CP violation (quark mixing) cannot account for observed baryon asymmetry
• experimental probes of the open questions

#1 is lepton number really violated? \{ neutrinoless double beta decay \}

#2 how are neutrino masses arranged?
#3 how many sterile neutrinos are there?
#4 is CP symmetry violated?

focus on accelerator based oscillation searches

see talks of: B. Jamieson  P. de Perio
H. Tanaka
A. Kanaka

active efforts also with atmospheric, reactor, supernova neutrinos

see talks of: D. Grant
C. Bruulsema

and theoretical interpretation

see talk of: N. Giasson
- \(0\nu\beta\beta\) experimental searches

11 candidate nuclei with observed double beta decay (single beta decay forbidden):

\[ ^{48}\text{Ca}, \, ^{76}\text{Ge}, \, ^{82}\text{Se}, \, ^{96}\text{Zr}, \, ^{100}\text{Mo}, \, ^{116}\text{Cd}, \, ^{128}\text{Te}, \, ^{130}\text{Te}, \, ^{136}\text{Xe}, \, ^{150}\text{Nd}, \, ^{238}\text{U} \]

\[ (T_{1/2}^{0\nu})^{-1} \propto |M^{0\nu}|^2 \langle m_{\beta\beta} \rangle^2 \]

\[ \langle m_{\beta\beta} \rangle^2 = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|^2 \]

- theory is critical to translate event rate to neutrino mass parameter
- \(O(1-10)\) uncertainty on matrix element, intense theory effort underway
• interplay of particle, nuclear, astro physics
• interplay of particle, nuclear, astro physics

![Diagram of neutrino mixing]

- Neutrino mixing
- Effective Majorana mass [eV]
- Lightest neutrino mass [eV]
- Normal hierarchy
- Inverted hierarchy
- Long baseline neutrino oscillations
- ~degenerate

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1e-05</td>
<td>0.0001</td>
<td>0.001</td>
</tr>
<tr>
<td>0.01</td>
<td>0.1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 13.10: The effective Majorana mass $|<m>|$ (including a 2σ uncertainty), as a function of $\min(m_j)$ for $\sin^2 13 = 0.0236 \pm 0.0042$ and $\delta = 0$. The figure is obtained using also the best fit values and 1σ errors of $\Delta m^2_{21}$, $\sin^2 12$, and $|\Delta m^2_{31}| \approx |\Delta m^2_{32}|$ from Ref. 140 (given in Table 13.7). For $\sin^2 12$ the results found with the “old” reactor $\bar{\nu}_e$ fluxes [35] were employed. The phases $\alpha_{21}$, $\alpha_{31}$ are varied in the interval [0, $\pi$]. The predictions for the NH, IH and QD spectra are indicated. The red regions correspond to at least one of the phases $\alpha_{21}$, $\alpha_{31}$ and $(\alpha_{31} - \alpha_{21})$ having a CP violating value, while the blue and green areas correspond to $\alpha_{21}$, $\alpha_{31}$ possessing CP conserving values. (Update by S. Pascoli of a figure from the last article quoted in Ref. 160.)

$A(\beta\beta)_0$-decay and the measurement of the corresponding half-life with sufficient accuracy, would not only be a proof that the total lepton charge is not conserved, but might also provide unique information on the i) type of neutrino mass spectrum (see, e.g., Ref. 158), ii) Majorana phases in $U_{144,159}$ and iii) the absolute scale of neutrino masses (for details see Ref. 157 to Ref. 160 and references quoted therein). Under the assumptions of 3-$\nu$ mixing, of massive neutrinos $\nu_j$ being Majorana particles, and of $A(\beta\beta)_0$-decay generated only by the (V-A) charged current weak interaction via the exchange of the three Majorana neutrinos $\nu_j$ having masses $m_j \ll$ few MeV, the $A(\beta\beta)_0$-decay amplitude has the form (see, e.g., Ref. 39 and Ref. 157):

$A(\beta\beta)_0 \sim <m> \cdot M$, where $M$ is the corresponding nuclear matrix element which does
- interplay of particle, nuclear, astro physics
• 0νββ experimental searches

K. Scholberg

The “Brute Force” Approach

The “Peak-Squeezer” Approach

The “Final-State Judgement” Approach

KamLAND-Zen

SNO+ (136 Xe)

CUORICINO/CUORE (130 Te)

MAJORANA (76 Ge)

GERDA (76 Ge)

EXO/nEXO (136 Xe)

NEMO/ SuperNEMO (various/82 Se)

NEXT (136 Xe)

+more future ideas...

C. Kraus  E. Caden  T. Brunner
J. Rumleskie  E. Cudmore  Y. Lan
R. Ford  R. Gornea  F. Retiere
long baseline neutrino oscillations

- $\nu_\mu$ produced by accelerator beams
- Appearance of $\nu_e$ as a function of neutrino energy and oscillation length probes underlying neutrino parameters

two important aspects:

1) long baseline to probe matter effect

\[ H = \sum_i \sqrt{m_i^2 + p^2} |\nu_i\rangle \langle \nu_i| + V(r)|\nu_e\rangle \langle \nu_e| \]

2) broad energy range to disentangle ordering, CP violation
1) long baseline to probe matter effect

\[ \nu_{\mu} \rightarrow \nu_e \text{ OSCILLATION PROBABILITY} \]

\[ \nu_{\mu} \rightarrow \nu_e \]

Neutrino, Normal Hierarchy

\[ \nu_{\mu} \rightarrow \nu_e \text{ (GeV)} \]

\[ \nu_{\mu} \rightarrow \nu_e \text{ (GeV)} \]

Neutrino, Normal Hierarchy

\[ \nu_{\mu} \rightarrow \nu_e \]

Antineutrino, Normal Hierarchy

\[ \bar{\nu}_{\mu} \rightarrow \bar{\nu}_e \]

Antineutrino, Normal Hierarchy

\[ \bar{\nu}_{\mu} \rightarrow \bar{\nu}_e \]

\[ \theta_{23}, \pi/4, 0, -\pi/2, +\pi/2, \pi, \delta_{CP}, \text{ NH, IH, Hierarchy} \]

\[ 295 \text{ km} \]
1) long baseline to probe matter effect

\[ \nu_\mu \rightarrow \nu_e \text{ OSCILLATION PROBABILITY} \]

295 km

\[ L \rightarrow 810 \text{ km} \]

\[ \nu_\mu \rightarrow \nu_e \]

Neutrino, Normal Hierarchy

\[ \frac{\pi}{4} \]

\[ \theta_{23} \]

\[ -\frac{\pi}{2} \rightarrow +\frac{\pi}{2} \]

\[ \delta_{\text{CP}} \]

\[ \text{NH} \rightarrow \text{IH} \]

Antineutrino, Normal Hierarchy

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

H. Tanaka
2) broad energy range to disentangle ordering, CP violation

$$\nu_\mu \rightarrow \nu_e \quad \text{OSCILLATION PROBABILITY}$$

$$\theta_{23}$$

$$\pi/4$$

$$0$$

$$-\pi/2$$

$$+\pi/2$$

$$\Delta$$

$$\delta_{\text{CP}}$$

$$\pi$$

$$\pi/2$$

$$-\pi/2$$

$$\text{Normal Hierarchy}$$

$$\text{Antineutrino, Normal Hierarchy}$$

$$\text{NH}$$

$$\text{IH}$$

$$\text{Hierarchy}$$

$$295 \text{ km}$$

$$\nu_\mu \rightarrow \nu_e$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

$$\text{H. Tanaka}$$
2) broad energy range to disentangle ordering, CP violation

\[ \nu_\mu \rightarrow \nu_e \text{ OSCILLATION PROBABILITY} \]

295 km

Neutrino, Normal Hierarchy

\[ \nu_\mu \rightarrow \nu_e \]

\[ \pi/4 \]

\[ 0 \]

\[ -\pi/2 \]

\[ +\pi/2 \]

\[ \theta_{23} \]

\[ \delta_{\text{CP}} \]

Normal Hierarchy

\[ \delta_{\text{CP}} = 0 \]

\[ \delta_{\text{CP}} = \pi \]

Antineutrino, Normal Hierarchy

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

\[ \pi/4 \]

\[ 0 \]

\[ -\pi/2 \]

\[ +\pi/2 \]

\[ \pi \]

\[ \theta_{23} \]

\[ \delta_{\text{CP}} \]

NH

IH

Hierarchy

H. Tanaka
2) broad energy range to disentangle ordering, CP violation

\[ \nu_\mu \rightarrow \nu_e \] Oscillation Probability

295 km

Neutrino, Normal Hierarchy

Antineutrino, Normal Hierarchy

\[ \nu_\mu \rightarrow \nu_e \] Normal Hierarchy

\[ \nu_\mu \rightarrow \nu_e \] Normal Hierarchy

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \] Normal Hierarchy

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \] Normal Hierarchy

\[ \theta_{23} \]

\[ \delta_{CP} \]

\[ \pi \]

\[ \pi/4 \]

\[ 0 \]

\[ -\pi/2 \]

\[ +\pi/2 \]

NH

IH

Hierarchy

H. Tanaka
probability of $\nu_\mu \rightarrow \nu_e \Rightarrow$ fundamental neutrino properties

$\nu_\mu$ flux $\nu_e$ flux = $\frac{\nu_e$ event rate}{cross section}$

E.g. DUNE

Cross section translates observed event rate to $\nu_e$ appearance prob.
probability of $\nu_\mu \rightarrow \nu_e \Rightarrow$ fundamental neutrino properties

$\nu_\mu$ flux $\xrightarrow{V_\mu} \nu_e$ flux $= \frac{\nu_e$ event rate}{cross section}$

Cross section translates observed event rate to $\nu_e$ appearance prob.

Basic signal process: charged current quasi elastic scattering
(large event sample, “reconstructible” neutrino energy, theoretically “clean”)
probability of $\nu_\mu \rightarrow \nu_e \Rightarrow$ fundamental neutrino properties

$\nu_\mu$ flux $\quad \nu_e$ flux $= \frac{\nu_e \text{ event rate}}{\text{cross section}}$ $\nu_e$ flux

E.g. DUNE

Cross section translates observed event rate to $\nu_e$ appearance prob.

**Basic signal process:** charged current quasi elastic scattering

*(large event sample, “reconstructible” neutrino energy, theoretically “clean”)*
probability of $\nu_\mu \rightarrow \nu_e \Rightarrow$ fundamental neutrino properties

$\nu_\mu$ flux

$\nu_e$ flux = $\frac{\nu_e$ event rate}{cross section}$

E.g. DUNE

Cross section translates observed event rate to $\nu_e$ appearance prob.

Basic signal process: charged current quasi elastic scattering

(large event sample, “reconstructible” neutrino energy, theoretically “clean”)
probability of $\nu_\mu \rightarrow \nu_e \Rightarrow$ fundamental neutrino properties

$\nu_\mu$ flux $\nu_e$ flux = $\frac{\nu_e$ event rate $\nu_e$ appearance prob.}{cross section}$

Cross section translates observed event rate to $\nu_e$ appearance prob.

Basic signal process: charged current quasi elastic scattering (large event sample, “reconstructible” neutrino energy, theoretically “clean”)

nuclear effects

hadronic amplitudes

E.g. DUNE

FERMILAB Batavia, Illinois

SANFORD LAB Lead, South Dakota
Neutrino Mixing, Mass Hierarchy, and CP Violation

where the LBNE neutrino beam spectrum peaks. The wide coverage of the oscillation patterns enables the search for physics beyond the three-flavor model because new physics effects may interfere with the standard oscillations and induce a distortion in the oscillation patterns. As a next-generation neutrino oscillation experiment, LBNE aims to study in detail the spectral shape of neutrino mixing over the range of energies where the mixing effects are largest. This is crucial for advancing the science beyond the current generation of experiments, which depend primarily on rate asymmetries.

Figure 4.1: The simulated unoscillated spectrum of $\nu_\mu$ events from the LBNE beam (black histogram) overlaid with the $\nu_\mu$ oscillation probabilities (colored curves) for different values of $\delta_{CP}$ and normal hierarchy.

The LBNE reconfiguration study [25] determined that the far detector location at the Sanford Underground Research Facility provides an optimal baseline for precision measurement of neutrino oscillations using a conventional neutrino beam from Fermilab. The 1,300 km baseline optimizes sensitivity to CP violation and is long enough to resolve the MH with a high level of confidence, as shown in Figure 2.7.

Table 4.1 lists the beam neutrino interaction rates for all three known species of neutrinos as expected at the LBNE far detector. This table shows only the raw interaction rates using the neutrino flux from the Geant4 simulations of the LBNE beamline and the default interaction cross sections included in the GLoBeS package [130] with no detector effects included. A tunable LBNE beam spectrum, obtained by varying the distance between the target and the first focusing horn (Horn 1), is assumed. The higher-energy tunes are chosen to enhance the appearance signal and improve the oscillation fits to the three-flavor paradigm. To estimate the NC event rates based on visible...
Neutrino Mixing, Mass Hierarchy, and CP Violation

Baseline, there is no degeneracy between matter and CP asymmetries at the first oscillation node where the LBNE neutrino beam spectrum peaks. The wide coverage of the oscillation patterns enables the search for physics beyond the three-flavor model because new physics effects may interfere with the standard oscillations and induce a distortion in the oscillation patterns. As a next-generation neutrino oscillation experiment, LBNE aims to study in detail the spectral shape of neutrino mixing over the range of energies where the mixing effects are largest. This is crucial for advancing the science beyond the current generation of experiments, which depend primarily on rate asymmetries.

Figure 4.1: The simulated unoscillated spectrum of $\bar{\nu}_\mu$ events from the LBNE beam (black histogram) overlaid with the $\bar{\nu}_\mu$ oscillation probabilities (colored curves) for different values of $\delta$ and normal hierarchy.

The LBNE reconfiguration study [25] determined that the far detector location at the Sanford Underground Research Facility provides an optimal baseline for precision measurement of neutrino oscillations using a conventional neutrino beam from Fermilab. The 1,300 $\neq$ km baseline optimizes sensitivity to CP violation and is long enough to resolve the MH with a high level of confidence, as shown in Figure 2.7.

Table 4.1 lists the beam neutrino interaction rates for all three known species of neutrinos as expected at the LBNE far detector. This table shows only the raw interaction rates using the neutrino flux from the Geant4 simulations of the LBNE beamline and the default interaction cross sections included in the GLoBeS package [130] with no detector effects included. A tunable LBNE beam spectrum, obtained by varying the distance between the target and the first focusing horn (Horn 1), is assumed. The higher-energy tunes are chosen to enhance the $\bar{\nu}_\mu$ appearance signal and improve the oscillation fits to the three-flavor paradigm. To estimate the NC event rates based on visible

Need precise cross section normalization

LBNE, 1307.7335
cf. Coloma, Huber et al., 1307.1243, 1311.4506; Lalakulich and Mosel, 1311.7288
Neutrino Mixing, Mass Hierarchy, and CP Violation

Baseline, there is no degeneracy between matter and CP asymmetries at the first oscillation node where the LBNE neutrino beam spectrum peaks. The wide coverage of the oscillation patterns enables the search for physics beyond the three-flavor model because new physics effects may interfere with the standard oscillations and induce a distortion in the oscillation patterns. As a next-generation neutrino oscillation experiment, LBNE aims to study in detail the spectral shape of neutrino mixing over the range of energies where the mixing effects are largest. This is crucial for advancing the science beyond the current generation of experiments, which depend primarily on rate asymmetries.

Figure 4.1: The simulated unoscillated spectrum of $\nu_\mu$ events from the LBNE beam (black histogram) overlaid with the $\nu_\mu$ appearance oscillation probabilities (colored curves) for different values of $\delta_{CP}$ and normal hierarchy.

The LBNE reconfiguration study [25] determined that the far detector location at the Sanford Underground Research Facility provides an optimal baseline for precision measurement of neutrino oscillations using a conventional neutrino beam from Fermilab. The 1,300 $\neq$ km baseline optimizes sensitivity to CP violation and is long enough to resolve the MH with a high level of confidence, as shown in Figure 2.7.

Table 4.1 lists the beam neutrino interaction rates for all three known species of neutrinos as expected at the LBNE far detector. This table shows only the raw interaction rates using the neutrino flux from the Geant4 simulations of the LBNE beamline and the default interaction cross sections included in the GLoBES package [130] with no detector effects included. A tunable LBNE beam spectrum, obtained by varying the distance between the target and the first focusing horn (Horn 1), is assumed. The higher-energy tunes are chosen to enhance the appearance signal and improve the oscillation fits to the three-flavor paradigm. To estimate the NC event rates based on visible
Cross section uncertainties can mimic the effects of CP violation:

\[
\sigma(E_\nu) \propto E_\nu^{-1/2} \bar{\nu}_p \rightarrow \mu_n (E_\bar{\nu} = 1 \text{ GeV}) = 3.83(23) \times 10^{-39} \text{ cm}^2 \]

\[
\bar{\nu}_p \rightarrow \mu_n (E_\bar{\nu} = 3 \text{ GeV}) = 6.47(47) \times 10^{-39} \text{ cm}^2 \]

- careful analysis of previous elementary target (deuterium) data reveals hadronic uncertainty. Future improvement from lattice QCD.

- intense theoretical effort underway
QCD in many regimes critical to extracting fundamental physics in the neutrino sector

An intense, interdisciplinary effort
Summary

• neutrino mass is physics beyond the standard model

• compelling questions remain unanswered

• theory has a critical role to play

• exciting interplay between particle and astrophysics

• next generation experiments are poised for discovery