Where These New Frontiers Can Come

From $\nu$–Physics?

A. Bettini
G. Galilei Physics and Astronomy Dept. Padua University. Italy
INFN Padova
The Nobel Prize for Physics 2015

Arthur McDonald and Takaaki Kajita
for the discovery of neutrino oscillations, which shows that neutrinos have mass
Summary

• Neutrino oscillations and flavour conversion in matter
  • Basic formalism
  • Present status
• Dirac and Majorana equations
• Recent results on
  • Electron antineutrino disappearance
  • Electron neutrino appearance
  • Neutrino-less double beta decay
• Experiments under construction
• Perspectives
Neutrino flavours

Definitions
\(\nu_e\) is the neutral particle produced with an \(e^+\) (e.g. \(\beta^+\) decay)
anti \(\nu_e\) is the neutral particle produced with an \(e^-\) (e.g. \(\beta^-\) decay)
Etc.

Neutrinos cannot be directly detected. The charged lepton produced by the neutrino interaction in the detector identifies by definition the neutrino flavour.

Question. Is the flavour at detection equal to that at production?

YES, if proper time elapsed is small
Neutrino flavour changes

Starting in the 1970s we learnt that neutrino change flavour, provided time (flight distance) is given them to do so

Two different processes

Oscillations and flavour conversion in matter, prove that neutrinos, contrary to the Standard model

- do not have zero mass
- flavour states are superposition (mixing) of mass eigenstates
Flavour states ≠ mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} & 0 \\ s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i(\beta+\delta)} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

9 quantities to be measured: 3 masses, 3 angles, 3 phases
4 known + 1 in absolute value

Two mechanisms observed changing neutrino flavour

- oscillation in vacuum (kinetic – interference phenomenon)
- transformation in matter MSW (Mikehev-Smirnov-Wolfestein) (dynamical – independent of the phase of wave function)
The mass spectrum

Oscillation probabilities do not depend at 1st order on sign of $\Delta m^2$ ("mass hierarchy") and sign of $(\theta - \pi/4)$
MSW depends on both signs
Oscillations probabilities at 2nd order depend on both signs

Indirect upper limits from cosmology
$m_i < 150$-$200$ meV

We do not know
The sign of the larger mass difference
The absolute values of the masses
Majorana or Dirac particle?
Neutrino spectrum and mixing

Best fit values and accuracies defined as 1/6 of ±3σ range

\[ \delta m^2 = 73.7 \text{ meV}^2 \quad 2.4 \% \]
\[ |\Delta m^2| = 2500 \text{ meV}^2 \quad (\text{NH}) \quad 1.8 \% \]
\[ 2460 \text{ meV}^2 \quad (\text{IH}) \]

\[ \sin^2 \theta_{12} = 0.297 \quad 5.8 \% \]
\[ \sin^2 \theta_{23} = 0.437 \quad (\text{NH}) \quad 9 \% \]
\[ 0.569 \quad (\text{IH}) \]
\[ \sin^2 \theta_{13} = 0.0214 \quad (\text{NH}) \quad 4.7 \% \]
\[ 0.0218 \quad (\text{IH}) \]
Is neutrino completely neutral?

V–A only left-handed neutrinos (eigenstates of $\gamma_5$ with eigenvalue $–1$)

$$\nu_e = \text{neutral particle produced with } e^+.$$

Dominant negative helicity + $m/E$ positive helicity

$\overline{\nu}_e = \text{neutral particle produced with } e^-$

Dominant positive helicity + $m/E$ negative helicity

<table>
<thead>
<tr>
<th>Dirac</th>
<th>Produces $e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$m/E$</td>
</tr>
<tr>
<td>$\overline{\nu}_e$</td>
<td>$m/E$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Majorana</th>
<th>Produces $e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$m/E$</td>
</tr>
<tr>
<td>$\overline{\nu}_e$</td>
<td>$m/E$</td>
</tr>
</tbody>
</table>

Only the extremely small $m/E$ component distinguishes between Dirac and Majorana

$E_\nu = 10 \text{ MeV}, m = 100 \text{ meV} \Rightarrow (m/E_\nu)^2 = 10^{-14}$

$\nu_e$ not producing $e^+$ do not prove lepton number conservation

Best present limits

$^{136}\text{Xe KL-ZEN } T_{1/2} > 1.1 \times 10^{26} \text{ yr}$

$^{136}\text{Xe EXO-200 } T_{1/2} > 2 \times 10^{25} \text{ yr}$

$^{76}\text{Ge GERDA Ph1 } T_{1/2} > 2 \times 10^{25} \text{ yr}$

Sensitivity of experiments in preparation: $10^{27} \text{ yr}$.
The Majorana equation

Dirac equation \[ (i\gamma^\mu \partial_\mu - m)\psi(x) = 0 \]  The \( \psi \) bi-spinor has 4 complex components

The 4 degrees of freedom correspond to the two helicity states of electron and positron

Only the anticommutators of the \( \gamma \) matrices are defined (Clifford algebra)

Majorana question: can \( \gamma \) matrices be chosen such as to have \( \psi \) real? \[ \{\gamma_\mu, \gamma_\nu\} = 2\eta_{\mu\nu} \]

Answer: the following obey Clifford algebra and are imaginary

\[ \tilde{\gamma}_0 = \sigma_2 \otimes \sigma_1, \quad \tilde{\gamma}_1 = i\sigma_1 \otimes 1, \quad \tilde{\gamma}_2 = i\sigma_3 \otimes 1, \quad \tilde{\gamma}_3 = i\sigma_2 \otimes \sigma_2 \]

\[ (i\tilde{\gamma}^\mu \partial_\mu - m)\tilde{\psi}(x) = 0 \]  all the \( i\tilde{\gamma}_\mu \) beam real, it can govern a \( \tilde{\psi} \) with all real components

Only 2 independent components, the two helicity states. Particle=antiparticle

Majorana particles are completely neutral spin 1/2 particles (like \( \gamma, Z, H \) etc. for bosons)

Must be massive
Two types of experiments

Two types of experiment

• **appearance of a different flavour**
  - far detector must be sensitive to the new flavour

• **disappearance of the initial flavour**
  - initial flux, composition and spectrum must be accurately known

Smallness of two quantities decouples short and long period oscillations & matter transformations at 1\textsuperscript{st} order

\[
\alpha \equiv \frac{|\delta m^2|}{\Delta m^2} \approx 0.03
\]

\[
\theta_{13}^2 \approx 0.024
\]

\[
P(\nu_x \rightarrow \nu_y, L) = A(\nu_x \rightarrow \nu_y) \sin^2 \left( 1.27 \Delta m^2 \left( \text{eV}^2 \right) \frac{L(\text{km})}{E(\text{GeV})} \right)
\]

\[
P(\nu_x \rightarrow \nu_y, L) = A(\nu_x \rightarrow \nu_y) \sin^2 \left( 1.27 \delta m^2 \left( \text{eV}^2 \right) \frac{L(\text{km})}{E(\text{GeV})} \right)
\]
First order amplitudes

Shorter period oscillation (“atmospheric”)

\[ P(\nu_x \to \nu_y, L) = A(\nu_x \to \nu_y) \sin^2 \left( 1.27\Delta m^2 \frac{L(\text{km})}{E(\text{GeV})} \right) \]

\[ A(\nu_\mu \to \nu_x) = \sin^2(2\theta_{23}) \cos^2(\theta_{13})(1 - \sin^2 \theta_{23} \cos^2 \theta_{13}) \approx \frac{1}{2} \quad \text{Disappearance. Atmospheric} \]

\[ A(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \approx 1 \quad \text{Dominant. Appearance. Observed by OPERA} \]

\[ A(\nu_\mu \to \nu_e) = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \approx 2\theta_{13}^2 \quad \text{Rare. Appearance. Observed by T2K and NOvA} \]

\[ A(\nu_e \to \nu_x) = \sin^2(2\theta_{13}) \approx 4\theta_{13}^2 \quad \text{Disappearance. Observed by DayaBay, Reno, DChooz} \]

Longer period oscillation (“solar”)

\[ P(\nu_e \to \nu_e) = c_{13}^4 \left( 1 - \sin^2 2\theta_{12} \sin^2 \left( 1.27\delta m^2 \frac{L}{E} \right) \right) + s_{13}^4 \approx 1 - \sin^2 2\theta_{12} \sin^2 \left( 1.27\delta m^2 \frac{L}{E} \right) \]

\[ \text{Disappearance. Solar, Reactor} \]
MSW effect in the Sun

In the core of the sun $\nu_e$ is mass eigenstate $\tilde{\nu}_2$

$$A = 2\sqrt{2} G_F N_e E$$
**Dirac phase**

Two complementary sources of experimental information

A disappearance probability = complement to 1 of remaining with the original flavour

Does not change under T. Hence CPT implies independence on Dirac phase

\[
P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27\Delta m^2 \frac{L}{E}\right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(1.27\delta m^2 \frac{L}{E}\right)
\]

Electron neutrino appearance on \(\nu_\mu\) beam. Expand in \(\alpha\) up to \(\alpha^2\) in vacuum

Define \(\Delta \equiv \Delta m^2_{31}\), \(\Delta m^2_{21} = \alpha\Delta = 0.03\Delta\), \(\Delta m^2_{32} = (1-\alpha)\Delta\)

\[
P(\nu_\mu \rightarrow \nu_e) = P_0 + P_{\sin \delta} + P_{\cos \delta} + P_3
\]

\[
P_0 = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(1.27\Delta \frac{L}{E}\right)
\]

\[
P_{\sin \delta} = \pm \alpha \times \sin \delta \times \cos \theta_{13} \times \sin 2\theta_{12} \times \sin 2\theta_{23} \times \sin 2\theta_{13} \times \sin^3 \left(1.27\Delta \frac{L}{E}\right) \quad + \text{for } \nu
\]

\[
P_{\cos \delta} = \alpha \times \cos \delta \times \cos \theta_{13} \times \sin 2\theta_{12} \times \sin 2\theta_{23} \times \sin 2\theta_{13} \times \cos \left(1.27\Delta \frac{L}{E}\right) \sin^2 \left(1.27\Delta \frac{L}{E}\right) \quad - \text{for } \bar{\nu}
\]

\[
P_3 = \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \left(1.27\Delta \frac{L}{E}\right)
\]

Matter is not CP symmetric. Matter effects give additional dependence on flight length and matter density.


22 June 2016
A. Bettini. Padova University and INFN
$\theta_{13}$ from reactor anti-nue disappearance

Daya Bay
Daya Bay

1660 m from LA
1900 m from DYB
Overburden 350 m

Eight 20 t “equal” detectors
Gd loaded Liquid Scintillator
Six power cores (17.4 GWth)
REDUNDANCY
**Gd doped liquid scintillator technique**

Inverse Beta Decay (IBD)  \( \bar{\nu}_e + p \rightarrow n + e^+ \)

**Prompt signal** = light from \( e^+ \) annihilation

**Delayed signal** (n capture) = \( \gamma \)s from Gd (nGd: 8MeV, 30 \( \mu \)s) from H (nH: 2.2 MeV, 100 \( \mu \)s)

\[
E_\nu \approx E_{prop} + \langle E_n \rangle + 0.78 \text{ MeV}
\]

- **Target** = Internal Acrylic Vessel Gd doped LS
  - 20 t of Gd (0.1% by mass)

- **\( \gamma \) catcher** = Outer Acrylic Vessel undoped LS
  - 22 t, detecting \( \gamma \)s escaped from IAV

- Stainless Steel Vessel with PMs
  - 36 t mineral oil, shields radiation from SSV and PMs

- **Inner and outer water shields** (Cherenkov)

- **Muon veto** roof
Daya Bay nGd


All 8 antineutrino detectors installed 2012
Reactor flux uncertainty. Relative measurements
Exposure of $6.9 \times 10^5$ GW$_{th}$-ton-days
Energy scale variations between detectors $< 0.2\%$

$$\sin^2 2\theta_{13} = 0.0840 \pm 0.005$$
DayaBay nH

$\gamma$ Energy from n capture on H < on Gd (2.2 vs 8 MeV) but on larger volume (IAV + OAV)

$\sin^2 2\theta_{13} = 0.071\pm0.011$

$\sin^2 2\theta_{13} = 0.084\pm0.005$

Comb. $\sin^2 2\theta_{13} = 0.082\pm0.004$

$<\text{far/near}> (\text{nGd}) = 0.948$

$<\text{far/near}> (\text{nH}) = 0.950$
Two identical Gd doped (16 t) Liquid Scintillator detectors, at 291 m (46 m deep) and 1380 m (168 m deep) from the center of six reactor cores of pressurized water reactors (2.8 GWth max each) spanning 1.3 km with equal spacing.
$\sin^2 2\theta_{13} = 0.082 \pm 0.009\text{(stat)} \pm 0.006\text{(syst)}$
T2K experiment
T2K experiment

T2K is a long-baseline neutrino experiment with a 600 MeV narrow band muon neutrino beam

- Detectors 2.5° off axis from neutrino beam
- Near detector at 280 m from beam source
- Far detector 295 km from source

Neutrino energy spectrum tuned to hit oscillation maximum at far detector

Form Christine Nielsen Moriond EW 2016
T2K. Near detectors

Provide info on flux and cross-sections. Differentiates between neutrino and antineutrino events. 0.2 T magnetic field. Constrains neutrino background for antineutrino oscillation analysis.
T2K Results on appearance
1311.4750 16 April 2014

6.39 \times 10^{20} \text{ protons on target in neutrino mode.}
Observed: \textbf{28 electron neutrinos} appearance. bkg 4.6\pm0.5
4.01 \times 10^{20} \text{ protons on target in antineutrino mode}
\textbf{3 electron antineutrinos} observed over 0.8 bkg
350 kW on target reached

Fit region < 1250 MeV

DayaBay 2016 1603.03549v2
Fermilab and NOvA
Fermilab NUMI beam
Fermilab NOvA

Modular construction
Tracking calorimeter
Liquid scintill. cells (3.9 cm x 6.6 cm x 15.5 m)
14 kt (10 kt fiducial)
300 kW, ramp to 700 kW
2.74x10^{20} \text{ protons-on-target}
250-400 kW on target
Full detector mass 14 kt
Observe 6 events; bkg: 0.99±0/11
Secondary analysis gives 11 events
No sensitivity yet, but more data are coming.
Longer baseline compared to T2K
increases sensitivity to the sign of $\Delta m^2$
Dirac Phase and matter effects

Difference between NH and IH depends on matter effect in earth
Constant density ≠ MSW
Measured by
\[ \nu \equiv \pm \frac{2\sqrt{2}G_F N_e E_\nu}{\Delta m^2_{13}} \]

T2K \( E = 0.6 \text{ GeV} \quad \nu \approx 0.05 \\
NO\nu A \quad E = 2 \text{ GeV} \quad \nu \approx 0.17

"Atmos" include recent SK and IC-deep core data

F. Capozzi et al. / Nuclear Physics B 00 (2016)
India based Neutrino Observatory. Sign of $\Delta m^2$

arXiv:1505.07380v1 [physics.ins-det]

Originally proposed by MONOLITH (LNGS P26/2000)

$$P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$

The surviving probabilities differ due to opposite matter potential (subdominant effect)

Effect depends on sign of $\Delta m^2_{13}$

Effect most important at MSW resonance

Magnetized Fe tracking calorimeter

Compare Down/Up vs. Zenith angle

Sensitivity to MH: $2 \sigma$ in 5 yr, $3 \sigma$ in 10 years

Also

ICECube PINGU
KM3NET ORCA
JUNO. Sign of $\Delta m^2$


Also
RENO-50
JUNO. Sign of $\Delta m^2$

Reactor electron antineutrino survival probability in vacuum

$$P_{ee} = 1 - c_{13}^4 \sin^2 \theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} \sin^2 |\Delta_{31}| - s_{12}^2 \sin^2 2\theta_{13} \sin^2 \Delta_{21} \cos |2\Delta_{31}|$$

$$\pm \frac{1}{2} \sin^2 2\theta_{13} \sin (2\Delta_{21}) \sin |2\Delta_{31}|$$

Big suppression due to the first term ("solar" oscillation)
Ripples due to the last term, encode the sign of $\Delta m^2$
Chose distance for maximum effect ($\approx 50$ km)
All source-detector distances should be equal
Energy resolution $\Delta E/E < 3\%/\sqrt{E}$ crucial and challenging
Dirac or Majorana?
Majorana neutrino couples to $W$ exactly as Dirac neutrino
The SM violation is in the propagator

The status created at one vertex has definite flavour, hence is a superposition of mass eigenstates
Mass eigenstates do not have definite helicity, are superpositions of Majorana neutrinos and antineutrinos
At one vertex the antineutrino component matters, the neutrino component at the other vertex

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

$$\nu_i \approx \frac{m_i}{E} \nu_{iL}^+ + \nu_{iL}^-$$

$$M_{ee} = |\sum_i U_{ei}^2 m_i| \approx \left| 0.67m_1 + 0.30m_2 e^{i2\alpha} + 0.03m_3 e^{i2(\beta-\delta)} \right|$$

Decay rate depends on nuclear physics
Nuclear matrix elements calculations have a typical uncertainty of 30%, for fixed $g_a$
NME depend on $g_a^4$
Experimental challenges

Move frontiers forward by
Energy resolution \(< 1\% \) FWHM
Background index \( \approx 0 \)
Look for scalability at ton scale
Source. Inner balloon (IB). $^{136}$Xe-loaded liquid scintillator
Active shield. Outer balloon (OB). Liquid scintillator

Fig. from A. Gando et al. Phys Rev. C 85, 045504 (2012)
Vertex distribution of candidate events (black points) and reproduced $^{214}$Bi background events in a MC simulation (color histogram) for $2.3 < E < 2.7$MeV (the $0\nu2\beta$ window). The solid and thick dashed lines indicate the shape of the IB and the 1-m-radius spherical volume, respectively.

The thin dashed lines illustrate the shape of the equal-volume spherical half-shells which compose the 2 m radius spherical fiducial volume for the $0\nu2\beta$ analysis.
**KAMLAND-ZEN**

**A. Bettini Padova University and INFN**

22-Jun-16

**Exposure= 504 kg yr**

\[ Q_{\beta\beta} = 2457.83 \pm 0.37 \text{ keV} \]

**Energy resolution FWHM = 270 keV**

**BI=(1–0.4)\times10^{-3} \text{ counts/(keVkg yr)} in the inner 1 m (period 1 –2)**

**\( T_{1/2} > 1.1 \times 10^{26} \text{ yr (90\% cl)} \)**

**Energy spectra within 1 m radius and fit results**

**arXiv:1605.02889 [hep-ex]**
KAMLAND-Zen
dominant background sources

Future
Larger and cleaner IB
LS doped with 800 kg of $^{136}$Xe
Improve spallation cuts
Improve energy resolution

$^{10}$C produced by $\mu$ spallation

$^{214}$Bi ($^{238}$U series) in IB nylon film

Limit of $0\nu\beta\beta$

Tail of $2\nu\beta\beta$
Perspective

- Present frontiers being pushed forward
  - Sign ($\Delta m^2$)
    - LBL reactor experiments (JUNO (ready 2020), RENO50 (ready 2022))
    - Atmospheric neutrinos (SK, IC deep core)
    - Present LBL accelerator experiments (T2K, NOvA)
  - Dirac phase
    - Present LBL accelerator experiments (T2K, NOvA)
    - MBL reactor experiments (DB, RENO, DC)
  - Absolute mass scale
    - Cosmology (need better understanding of systematics)
    - DBD experiments (need better NME, clarify $g_a$ problem)
  - Nature of neutrinos
    - DBD experiments (10 meV scale requires $M=O(1 \text{ t})$ with $b<O(10^{-4})$)
  - Decisions on future accelerator experiments (BL length, WC vs Lar detector) needs input from running and near future experiments
    - Shall we know sign($\Delta m^2$)? If yes, base line few 100 km (WC)
    - Shall we approximately know Dirac phase? If yes, optimise BL and detector
  - Majorana phases will need exploiting the eV neutrino energy scale
THANK YOU