Neutrino Physics

Cyriana, Milad, Onno, Richard, Robert-Jan

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Outline

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Past decades	Experimental verification of neutrino oscillations
Ongoing	Open questions about: Sterile neutrinos, Majorana or Dirac, mass hierarchy, CP(T) violation

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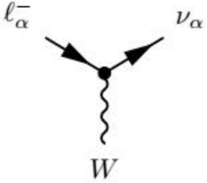
Neutrino oscillations

- In the SM neutrinos are massless and leptons do not mix.
- Pontecorvo proposed that $\nu \leftrightarrows \bar{\nu}$ transition may occur in analogy with $K^0 \leftrightarrows \bar{K}^0$ (1957). A quantitative theory of neutrino oscillations was first developed by Maki, Nakagawa and Sakata (1962).
- Predictions of the Standard Solar Model for the amount of ν_e were tested, of the expected flux of ν_e only $1/3$ found by the Homestake experiment in 1970s (SNP).
- Neutrino oscillations ($\nu_\alpha \rightarrow \nu_\beta$) were first measured by Super-Kamiokande in 1998 and later by SNO in 2001.

Neutrino flavors

- 3 neutrino flavors, ν_e, ν_μ and ν_τ are known, mixing of the 3 generations have been seen in many experiments.
- Definition of flavor: ν_α is the particle which couples to ℓ_α through weak interaction.
- flavor eigenstates , but mixed states of mass eigenstates (In SM flavor eigenstate = mass eigenstate).



Mixing matrix

Massive neutrinos imply the existence of right-handed neutrino components (minimally extended SM):

- Yukawa couplings are not diagonal anymore, mixing occurs.
- Introduce a unitary leptonic mixing matrix U like the CKM matrix for the quarks.

This matrix relates the flavor eigenstates to the mass eigenstates:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad (\alpha = e, \mu, \tau)$$

Parametrization of the mixing matrix

In general, a $N \times N$ unitary matrix has N^2 real parameters:

- $\frac{N(N+1)}{2}$ phases
- $\frac{N(N-1)}{2}$ angles

for 2N neutrino fields we can also eliminate $2N - 1$ unphysical phases by redefining the fields (leaving the Lagrangian invariant).

For a 3×3 matrix this leads to 3 angles and 1 phase.

2-generation mixing

A 2 × 2 unitary matrix can be written as matrix which depends on 3 phases ω_1, ω_2 and η and 1 angle θ

$$U = \begin{pmatrix} \cos\theta e i\omega_1 & \sin\theta e^{i(\omega_2+\eta)} \\ -\sin\theta e^{i(\omega_1-\eta)} & \cos\theta e^{i\omega_2} \end{pmatrix}$$

$$\sim \begin{pmatrix} \omega_1 & 0 \\ 0 & \omega_2 \end{pmatrix} \begin{pmatrix} e^{i\eta} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} e^{-i\eta} & 0 \\ 0 & 1 \end{pmatrix}$$

Four fields are present, flavor eigenstates ν_e, ν_μ and mass eigenstates ν_1, ν_2, so the 3 phases are not physical can be eliminated.

2-generation mixing

We are left with a rotation matrix to relate the flavor and mass eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

PMNS matrix

For 3 generations of leptons we have the Pontecorvo-Maki-Nakagawa-Sakata matrix[3]

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

with $c_{ab} \equiv \cos\theta_{ab}$ and $s_{ab} \equiv \sin\theta_{ab}$

θ_{ab} are mixing angles

δ is called CP-violating phase or Dirac phase.

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[3] A derivation can be found in [Giunti and Kim, 2007a].

PMNS matrix

If neutrinos are Majorana particles:

$$U = U^D \mathrm{diag}(1, e^{i\alpha_1}, e^{i\alpha_2})$$

There are two extra phases, called Majorana phases, because Majorana mass terms ($\frac{1}{2}\mathbf{n}_L^T C^\dagger M \mathbf{n}_L$) are not invariant under global U(1) gauge transformations.

Oscillation probability

Standard derivation of $P_{\nu_\alpha \to \nu_\beta}(t)$

- The mass eigenstates $|\nu_k\rangle$ are eigenstates of H, with energy $E_k = \sqrt{\mathbf{p}^2 + m^2}$
- Schrödinger equation implies $|\nu_k(t)\rangle = e^{-iE_k t}|\nu_k\rangle$
- $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$ and $|\nu_i\rangle = \sum_\alpha U_{\alpha i}|\nu_\alpha\rangle$

So the amplitude $A_{\nu_\alpha \to \nu_\beta}(t)$ is:

$$\begin{aligned} A_{\nu_\alpha \to \nu_\beta}(t) = \langle \nu_\beta | \nu_\alpha(t) \rangle &= \sum_\beta \left(\sum_k U^*_{\alpha k} e^{-iE_k t} U_{\beta k} \right) \langle \nu_\beta | \nu_\alpha \rangle \\ &= \sum_k U^*_{\alpha k} U_{\beta k} e^{-iE_k t} \end{aligned}$$

Oscillation probability

Probability of a transition $\nu_\alpha \to \nu_\beta$

$$P_{\nu_\alpha \to \nu_\beta}(t) = |A_{\nu_\alpha \to \nu_\beta}(t)|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} e^{-i(E_k - E_j)t}$$

For ultrarelativistic neutrinos we have that $E_k \simeq E + \frac{m_k^2}{2E}$ and that $t \sim L$:

$$P_{\nu_\alpha \to \nu_\beta}(t) = |A_{\nu_\alpha \to \nu_\beta}(t)|^2 = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

where $\Delta m^2_{kj} \equiv \Delta m^2_k - \Delta m^2_j$

Oscillation probability for antineutrinos

We can write the oscillation probability also in the form

$$\begin{aligned} P_{\nu_\alpha \to \nu_\beta}(t) = \delta_{\alpha\beta} &- 4 \sum_{k>j} \mathrm{Re}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) \\ &+ 2 \sum_{k>j} \mathrm{Im}\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right) \end{aligned}$$

Assuming CPT invariance:
For antineutrinos we have that $P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}(t)$ is the same up to a minus sign in third term.

Oscillations and CP-violation

- A CP transformation interchanges neutrinos with negative helicity and antineutrinos with positive helicity, so $\nu_\alpha \to \nu_\beta$ becomes $\bar{\nu}_\alpha \to \bar{\nu}_\beta$.
- This CP transformation changes $U \leftrightarrows U^*$.
- We saw that this leads to a difference in sign of the terms depending on the imaginary parts of $U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}$, leading to an asymmetry $A^{CP}_{\alpha\beta}(L, E)$:

Oscillations and CP-violation

$$A^{CP}_{\alpha\beta}(L,E) = 4\sum_{k>j}\mathrm{Im}\left[U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}\right]\sin\left(\frac{\Delta m^2_{kj}L}{2E}\right)$$

- $U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j}$ does not depend on the Majorana phases, so they do not influence the oscillations;
- it does only depend on δ, which is therefore also called the CP-violating phase.
- If U is real neutrino oscillations do not violate CP symmetry.

Oscillation probability

- If neutrinos are massless, $\Delta m^2_{kj} = 0$, hence there will be no oscillation.
- The phase $\Phi_{kj} = -\frac{\Delta m^2_{kj} L}{2E}$ of the oscillation depends on experimental variables L and E and constants Δm^2_{kj}.
- The amplitude $U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}$ depends on the elements of U.
- Absolute values of the masses cannot be determined measuring oscillations, but the mass difference can be determined.

$$P_{\nu_\alpha \to \nu_\beta}(t) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

Mass Hierarchy

- We can measure Δm_{kj}^2, however not the absolute values of the masses.
- The mass hierarchy of neutrinos is unknown.
- Depends on the sign of Δm_{13}^2 which has not yet been measured.

Three possible hierarchies: normal, inverted and degenerate:

- $m_1^2 \simeq m_2^2 < m_3^2$
- $m_1^2 \simeq m_2^2 > m_3^2$
- $m_1^2 \simeq m_2^2 \simeq m_3^2$ (excluded)

Degenerate hierarchy is excluded, since $\Delta m_{12}^2 < \Delta m_{23}^2$.

Neutrino squared-mass spectrum

$$\Delta m^2_{12} \equiv \Delta m^2_{\odot} \simeq 8.0 \times 10^{-5}\ \mathrm{eV}^2,\ \Delta m^2_{23} \equiv \Delta m^2_{atm} \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$$

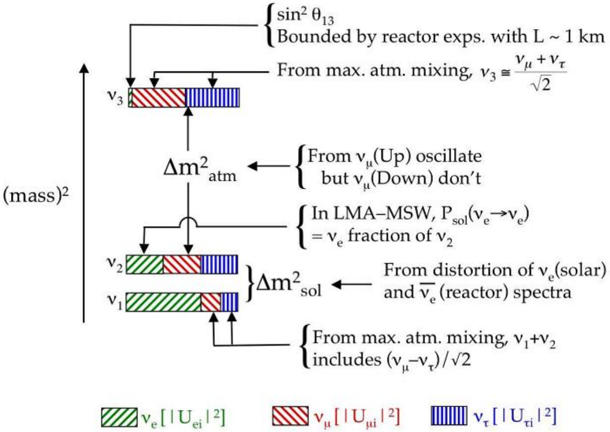

Figure : [Kayser, 2005]

Normal and inverted hierarchy

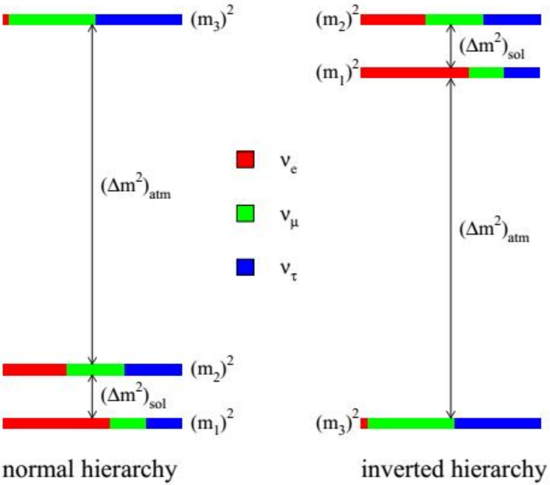

Figure : citeGouvea2005

Neutrino mass

Experiments have shown that neutrinos oscillate and have mass.
Some theoretical motivations for neutrino mass are:

- No fundamental theoretical reason to not introduce a right-handed neutrino field. This can give a mass term through the Higgs-mechanism. This is called the minimally extended SM.
- Unification of forces: a supersymmetrized version of the SM naturally predicts massive neutrinos (unless lepton number symmetry is imposed).

Higgs-lepton Lagrangian

Representation of Leptons in the SM [Giunti and Kim, 2007a]:

$$\begin{aligned} L_{L,\alpha} &= \begin{pmatrix} \nu_{\alpha,L} \\ \alpha_L \end{pmatrix} \text{ where } \alpha = e, \mu, \tau \\ \ell_{R,\alpha} &= \alpha_R \end{aligned}$$

$$\mathcal{L}_{H,L} = -\sum_\alpha Y^\ell_\alpha \left(\overline{L_{L,\alpha}} \phi \ell_{R,\alpha} + \overline{\ell_{R,\alpha}} \phi^\dagger L_{L,\alpha} \right) \text{ where } \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

So no neutrino mass:

$$\mathcal{L}_{H,L} = -\sum_\alpha \underbrace{\frac{y^\ell_\alpha v}{\sqrt{2}}}_{m_\alpha} \overline{\ell_{L,\alpha}} \ell_{R,\alpha} - \sum_\alpha \frac{y^\ell_\alpha}{\sqrt{2}} \overline{\ell_{L,\alpha}} \ell_{R,\alpha} H + \text{h.c.}$$

Massive Dirac Neutrinos

Introduce $\nu_{\alpha,R}$ with $\alpha = e, \mu, \tau$ (minimally extended Standard Model) [4]

- Singlet under $SU(3)_c \times SU(2)_L$ and Y=0
- Only interacts through gravity ⇒ sterile

This leads to an additional term in the Lagrangian:

$$\mathcal{L}_{H,L} = -\left(\frac{v+H}{\sqrt{2}}\right)\left(\sum_{\alpha=e,\mu,\tau} y^{\ell}_{\alpha}\overline{\ell_{L,\alpha}}\ell_{R,\alpha} + \sum_{k=1,2,3} y^{n}_{k}\overline{\nu_{L,k}}\nu_{R,k} + \mathrm{h.c}\right)$$

$$\Rightarrow \boxed{m_k = \frac{y^n_k v}{\sqrt{2}}}$$

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[4] In principle, there is no objection to only having 1 right-handed neutrino.

Neutrino flavor mixing

The above scenario allows for neutrino flavor mixing:

$$\boldsymbol{\nu}_L = U\mathbf{n}_L \text{ where } \boldsymbol{\nu}_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \text{ and } \mathbf{n}_L = \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

However, it does not:

- allow for mixing between neutrinos and sterile neutrinos ($\boldsymbol{\nu}_R$) → necessary?
- explain the small mass of neutrinos (i.e. the small value of y_k^n)

Possible solution: See-saw mechanism

Majorana Neutrinos

Majorana condition for a fermion field $\psi = \psi_L + \psi_R$:

- $\psi = \mathcal{C}\overline{\psi}^T$ or $\psi = \psi^C$

This is satisfied if one replaces $\psi_{R/L}$ by $\psi^C_{L/R}$ (or $\mathcal{C}\overline{\psi_{L/R}}^T$)[5]

The Majorana Lagrangian mass terms then becomes:

$$\begin{aligned}\mathcal{L}^L_{mass} &= -\frac{1}{2} m_L \overline{\nu^c_L} \nu_L + \mathrm{h.c} \\ \mathcal{L}^R_{mass} &= -\frac{1}{2} m_R \overline{\nu^c_R} \nu_R + \mathrm{h.c}\end{aligned}$$

and the Dirac Lagrangian as defined above:

$$\mathcal{L}^D_{mass} = -m_D \overline{\nu_R} \nu_L + \mathrm{h.c}$$

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[5] Require the field equations to be identical

Dirac-Majorana Lagrangian

The most general Dirac-Majorana Lagrangian for one generation:

$$\begin{aligned}
\mathcal{L}^{D+M}_{mass} &= \mathcal{L}^{D}_{mass} + \mathcal{L}^{L}_{mass} + \mathcal{L}^{R}_{mass} \\
&= -\frac{1}{2} m_D \overline{\nu_R} \nu_L - \frac{1}{2} m_L \overline{\nu_L^c} \nu_L - \frac{1}{2} m_R \overline{\nu_R^c} \nu_R + \mathrm{h.c} \\
&= -\frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \underbrace{\begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}}_{M} \underbrace{\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}}_{N_L} + \mathrm{h.c.}
\end{aligned}$$

In the SM:

- $m_L \neq 0$ not allowed, but can be generated by physics Beyond the Standard Model (BSM)
- $m_R \neq 0$ OK

Diagonalization of the mass matrix

We want to find the field of massive neutrinos, introduce unitary matrix U

- $U^T M^\dagger M U = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}^2$
- $N_L = U n_L$ where $n_L = \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \end{pmatrix}$

Moreover, this unitary matrix is given by,

$$U = \begin{pmatrix} \cos\theta e^{i\lambda} & \sin\theta \\ -\sin\theta e^{i\lambda} & \cos\theta \end{pmatrix}$$

where θ is the mixing angle and λ a CP-violating phase.
In general:

$$\tan 2\theta = \frac{2m_D}{m_R - \Re[m_L]}$$

Mass eigenstates

Introducing this unitary matrix:

$$\begin{aligned}\mathcal{L}_{mass}^{D+M} &= -\frac{1}{2}\begin{pmatrix}\overline{\nu_L^c} & \overline{\nu_R}\end{pmatrix}\underbrace{\begin{pmatrix}m_L & m_D\\ m_D & m_R\end{pmatrix}}_{M}\underbrace{\begin{pmatrix}\nu_L\\ \nu_R^c\end{pmatrix}}_{N_L}+\mathrm{h.c.}\\ &= -\frac{1}{2}\overline{N_L^c}MN_L+\ \mathrm{h.c}\\ &= -\frac{1}{2}\overline{N_L^c}UU^\dagger MUU^\dagger N_L+\ \mathrm{h.c}\\ &= -\frac{1}{2}\sum_{k=1,2} m_k\overline{\nu_{kL}^c}\nu_{kL}+\ \mathrm{h.c.}\end{aligned}$$

With $\nu_k = \nu_{kL} + \nu_{kL}^C$

See-Saw mechanism[6]

$m_D \ll m_R$ and $m_L = 0 \Longrightarrow M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$ Eigenvalues are: $m_1 \approx \frac{m_D^2}{m_R}$; $m_2 \approx m_R$

⇒ a very light neutrino and a massive sterile neutrino are created

Moreover, small mixing:

$$\tan 2\theta = \frac{2m_D}{m_R - \Re[m_L]} \Rightarrow \theta \ll 1$$

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[6] [Mulders, 2012, Giunti and Kim, 2007a]

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2 Theoretical Background
- Neutrino mixing
- Massive neutrinos
- Why neutrinos are always said to be left handed

3 Discussion: theory

4 Experiments
- Solar and atmospheric neutrinos
- Reactor experiments
- Accelerator experiments

5 Outlook

6 References

The handedness of neutrinos: helicity

Helicity is defined as:

$$\hat{h} = \frac{\vec{S} \cdot \vec{p}}{s\,|\vec{p}|} = \begin{cases} +1, & \text{right-handed } \bar{\nu} \\ -1, & \text{left-handed } \nu \end{cases}$$

Not Lorentz invariant!

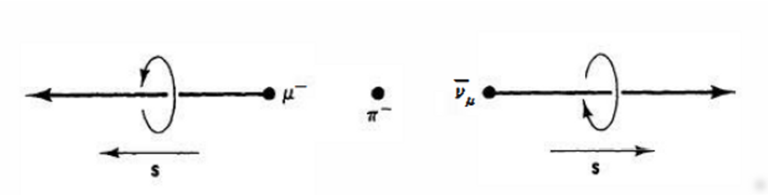


Figure : Pion back to back scattering: π^- has spin zero, μ^- experimentally turns out to always be right-handed ($h = +1$) [Griffiths, 2008].

Chirality: a different definition of handedness

Definition: eigenvalue of γ^5
For Weyl spinors (eigenfunctions of γ^5):

$$\left.\begin{array}{r}\gamma^5\psi_R = +\psi_R \\ \gamma^5\psi_L = -\psi_L\end{array}\right\} \Rightarrow \text{ neutrinos: again called right- and left-handed}$$

$$\left.\begin{array}{r}\gamma^5\overline{\psi_R} = -\overline{\psi_R} \\ \gamma^5\overline{\psi_L} = +\overline{\psi_L}\end{array}\right\} \Rightarrow \text{ anti neutrinos: left- and right-handed respectively}$$

Chirality <u>is</u> Lorentz invariant!

Relation between chirality and helicity for $m = 0$

Field equations:

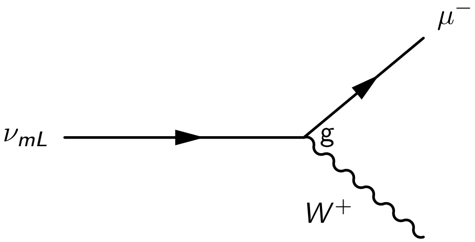
$$i\partial\!\!\!/\psi_{R/L} = m\psi_{L/R}$$

For massless fields one can show that:

$$\left.\begin{aligned} \hat{h}\psi_R &= +\psi_R \\ \hat{h}\psi_L &= -\psi_L \end{aligned}\right\} \Rightarrow \text{ for } m = 0 \text{ chirality} \leftrightarrow \text{helicity}$$

As you would expect, for $m = 0$ helicity is also Lorentz invariant!

Only left-chiral neutrinos



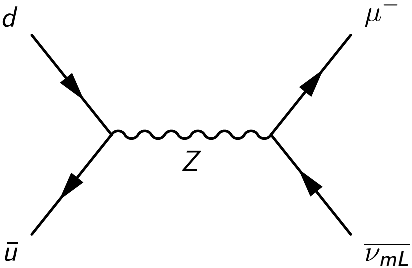
Let us only consider the μ neutrinos, we have in the simplest picture:

$$\nu_{mL} = \cos\theta\nu_L + \sin\theta\nu_R^c$$

Recall that $N_L = Un_L$!!

From this it is clear that in neutrino interaction we will only see left *chiral* massive neutrinos (vice versa for anti-neutrinos).

π^- decay



Since we have $\nu_L = U_{11}\nu_{1L} + U_{12}\nu_{2L}$

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   - Massive neutrinos
   - Why neutrinos are always said to be left handed
3. Discussion: theory
4. **Experiments**
   - Solar and atmospheric neutrinos
   - Reactor experiments
   - Accelerator experiments
5. Outlook
6. References

Introduction to experiments

Essentially two kinds of oscillations experiments

- Appearance measurements → measure transition probability
- Disappearance measurements → measure survival probability

$P \sim \sin^2\left(1.27\Delta m^2[\mathrm{eV}]^2\frac{\mathrm{L[km]}}{\mathrm{E[GeV]}}\right).$

- Not possible to measure flavor transitions if $\frac{\Delta m^2 L}{E} \ll 1$
- An average of $P_{\nu_\alpha \to \nu_\beta}$ can be measured when $\frac{\Delta m^2 L}{E} \gg 1$
- The sensivity to Δm^2 is the value Δm^2 for which $\frac{\Delta m^2 L}{E} \sim 1$.

Introduction to experiments

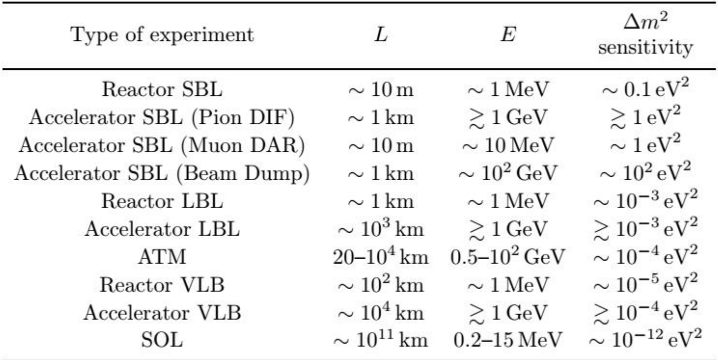
Types of experiments are

- Solar and atmospheric neutrino experiments
- Reactor experiments
- Accelerator experiments

These last two can be divided into groups based on source-detector distance L.

- short baseline
- long baseline
- very long baseline

Introduction to experiments



Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	$\sim 10\,\mathrm{m}$	$\sim 1\,\mathrm{MeV}$	$\sim 0.1\,\mathrm{eV}^2$
Accelerator SBL (Pion DIF)	$\sim 1\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 1\,\mathrm{eV}^2$
Accelerator SBL (Muon DAR)	$\sim 10\,\mathrm{m}$	$\sim 10\,\mathrm{MeV}$	$\sim 1\,\mathrm{eV}^2$
Accelerator SBL (Beam Dump)	$\sim 1\,\mathrm{km}$	$\sim 10^2\,\mathrm{GeV}$	$\sim 10^2\,\mathrm{eV}^2$
Reactor LBL	$\sim 1\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-3}\,\mathrm{eV}^2$
Accelerator LBL	$\sim 10^3\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-3}\,\mathrm{eV}^2$
ATM	$20\text{–}10^4\,\mathrm{km}$	$0.5\text{–}10^2\,\mathrm{GeV}$	$\sim 10^{-4}\,\mathrm{eV}^2$
Reactor VLB	$\sim 10^2\,\mathrm{km}$	$\sim 1\,\mathrm{MeV}$	$\sim 10^{-5}\,\mathrm{eV}^2$
Accelerator VLB	$\sim 10^4\,\mathrm{km}$	$\gtrsim 1\,\mathrm{GeV}$	$\gtrsim 10^{-4}\,\mathrm{eV}^2$
SOL	$\sim 10^{11}\,\mathrm{km}$	$0.2\text{–}15\,\mathrm{MeV}$	$\sim 10^{-12}\,\mathrm{eV}^2$

Figure : [Giunti and Kim, 2007a]

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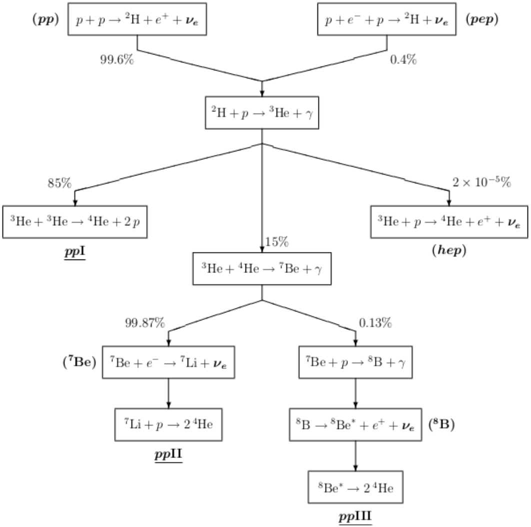
Solar Neutrinos



(*pp*) $p + p \to {}^2\mathrm{H} + e^+ + \nu_e$

(*pep*) $p + e^- + p \to {}^2\mathrm{H} + \nu_e$

99.6%

0.4%

${}^2\mathrm{H} + p \to {}^3\mathrm{He} + \gamma$

85%

15%

$2 \times 10^{-5}\%$

${}^3\mathrm{He} + {}^3\mathrm{He} \to {}^4\mathrm{He} + 2\,p$

***pp*I**

${}^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$

(*hep*)

${}^3\mathrm{He} + {}^4\mathrm{He} \to {}^7\mathrm{Be} + \gamma$

99.87%

0.13%

(^{7}Be) ${}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p \to {}^8\mathrm{B} + \gamma$

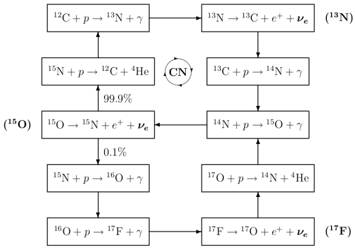
${}^7\mathrm{Li} + p \to 2\,{}^4\mathrm{He}$

***pp*II**

(^{8}B) ${}^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$

${}^8\mathrm{Be}^* \to 2\,{}^4\mathrm{He}$

***pp*III**



${}^{12}\mathrm{C} + p \to {}^{13}\mathrm{N} + \gamma$

${}^{13}\mathrm{N} \to {}^{13}\mathrm{C} + e^+ + \nu_e$ **(^{13}N)**

${}^{15}\mathrm{N} + p \to {}^{12}\mathrm{C} + {}^4\mathrm{He}$

CN

${}^{13}\mathrm{C} + p \to {}^{14}\mathrm{N} + \gamma$

99.9%

(^{15}O) ${}^{15}\mathrm{O} \to {}^{15}\mathrm{N} + e^+ + \nu_e$

${}^{14}\mathrm{N} + p \to {}^{15}\mathrm{O} + \gamma$

0.1%

${}^{15}\mathrm{N} + p \to {}^{16}\mathrm{O} + \gamma$

${}^{17}\mathrm{O} + p \to {}^{14}\mathrm{N} + {}^4\mathrm{He}$

${}^{16}\mathrm{O} + p \to {}^{17}\mathrm{F} + \gamma$

${}^{17}\mathrm{F} \to {}^{17}\mathrm{O} + e^+ + \nu_e$ **(^{17}F)**

Both
from [Giunti and Kim, 2007b]

Solar neutrino spectrum

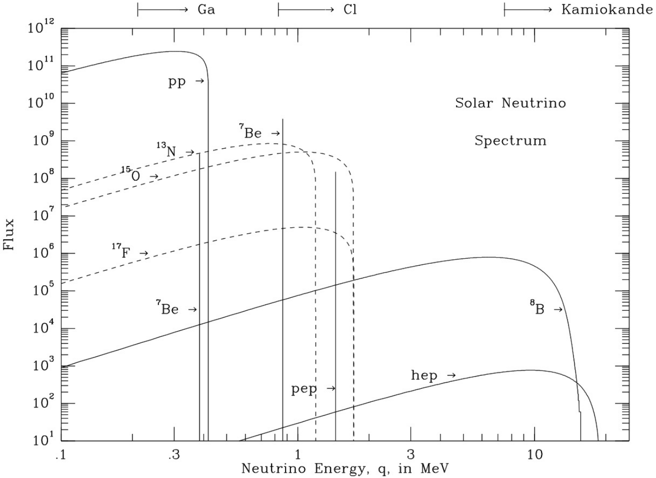


Figure : [Bahcall and Pinsonneault, 2004]

Solar Neutrino reactions

Solar neutrinos are captured via the following reactions:

- CC: $\nu_e + d \rightarrow p + p + e^-$
- NC: $\nu_\alpha + d \rightarrow p + n + \nu_\alpha$
- ES: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$ $(\sigma_{\nu_e} \approx 6\sigma_{\nu_{\mu,\tau}})$

Homestake

Homestake experiment used ^{37}Cl solved in water for CC-reaction:

$$\nu_e + {}^{37}Cl \to {}^{37}Ar + e^-$$

- ^{37}Ar-decay is measured.
- Threshold energy $\leq 0.814 MeV$, thus ^{8}B neutrinos are observed.
- Background: μ-decay from cosmic rays (0.08 ± 0.03 atoms/day)

Results

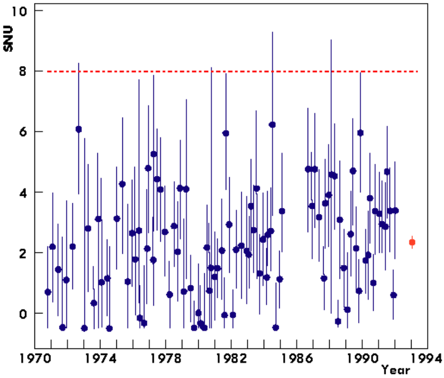


Figure : [Davis, 1994]

$1SNU = 10^{-36}\nu$ captures per target atom per second

SNO

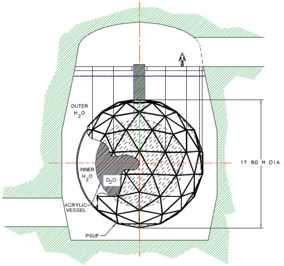


Figure : From [Boger et al., 2000]

- Neutral current, Charged current and electron-scattering are measured
- Isotropic γ's from NC neutron reactions are detected.
- E_γ well above background

SNO-results

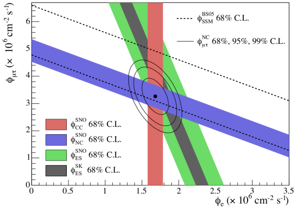


Figure : From [Giunti and Kim, 2007b]

- $\Phi_{CC} = 1.86 \pm 0.06 \cdot 10^6 cm^{-2} s^{-1}$
- $\Phi_{NC} = 4.94 \pm 0.21 \cdot 10^6 cm^{-2} s^{-1}$
- $\Phi_{ES} = 2.35 \pm 0.22 \cdot 10^6 cm^{-2} s^{-1}$

Implications

The solar mixing parameters are (best fit):

- $\Delta m^2_{\rm sol} = 7.1^{+1.0}_{-0.3} \cdot 10^{-5} eV^2$
- $\theta_{\rm sol} = 32.5^{+2.4\circ}_{-2.3}$

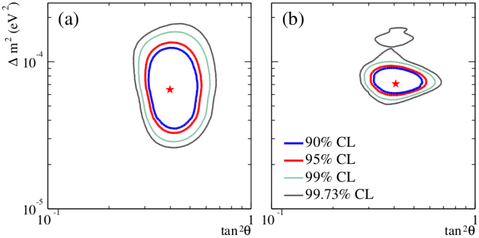


Figure : From [Ahmed et al., 2004]

Matter oscillations

Our distance to the sun (L) varies:

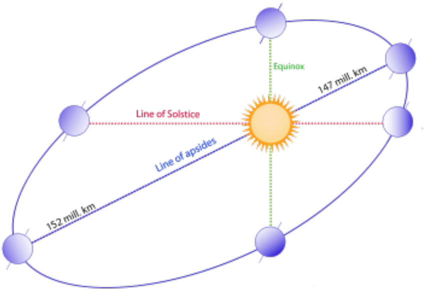


Figure : `http://en.wikipedia.org/wiki/File:Seasons1.svg`

- No seasonal effects to neutrino oscillations.
- flavor oscillations in vacuum no solution.
- Neutrino oscillations in matter.

Oscillations in Matter

- In matter, ν_e can interact with e^- via CC.
- All ν can interact via NC.
- Extra potential energy terms in Hamiltonian:

$$\mathbf{H}_M = \mathbf{H}_{\mathrm{vac}} + V_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + V_Z \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Where $V_W = \sqrt{2} G_F n_e$ due to CC and $V_z = -\frac{\sqrt{2}}{2} G_F n_n$ due to NC.

$\Rightarrow$ Different mixing probabilities and time effects

MSW-effect

Δm^2 and θ replaced by effective Δm^2_m and ${\theta_m}^7$:

$$\begin{aligned} \Delta m^2_m &\equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2} \\ \sin^2 2\theta_m &\equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \\ x &\equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2} \end{aligned}$$

⇒ Matter factor proportional to E and n_e.

---

[7] For a detailed derivation, see [Giunti and Kim, 2007b] or [Kayser, 2005]

Large Mixing Angle MSW-effect

- For ${}^{8}B\nu_e$ in the centre of the sun, the V_C term in the Hamiltonian dominates.

⇒ ν_e are born as eigenstates of this matrix with eigenvalue $\sqrt{2}G_F n_e$:

$$\mid \nu_e\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

- Propagating to the edge of the sun, the neutrino remains eigenstate of total $\mathbf{H}_M$, and thus emerges as upper eigenstate $\mid \nu_2\rangle$ of $\mathbf{H}_{\mathrm{vac}}$ from the sun.
- From there, it propagates as a normal $\mid \nu_2\rangle$ from the sun without oscillating.
- The probability that it interacts as ν_e on earth is thus proportional to $|U_{e2}|^2 = \theta_{sol} \cong \frac{1}{3}$, and does not oscillate with L

Cosmic rays react in the atmosphere

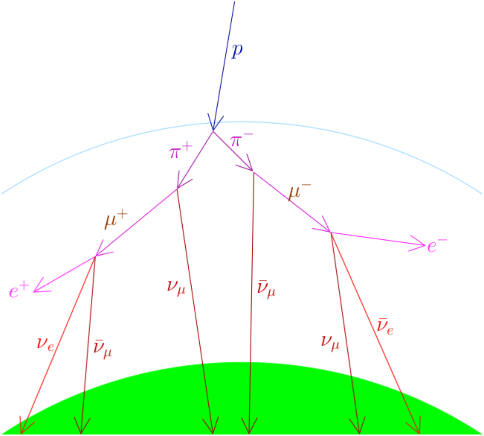


Figure : [Giunti and Kim, 2007b]

Main decays responsible for neutrinos:

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ or $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

Expected flux ratio:

$$\frac{\Phi_{\nu_\mu} + \Phi_{\bar{\nu}_\mu}}{\Phi_{\nu_e} + \Phi_{\bar{\nu}_e}} \approx 2$$

However, for $E_\mu \geq 1 GeV$, a portion of $\mu^\pm$ reaches the surface of the earth before escaping, thus:

$$\frac{\Phi_{\nu_\mu} + \Phi_{\bar{\nu}_\mu}}{\Phi_{\nu_e} + \Phi_{\bar{\nu}_e}} \geq 2$$

Detection of Atmospheric Neutrinos

Main reactions:

$$\nu_l + N \rightarrow l^- + X$$

$$\bar{\nu}_l + N \rightarrow l^+ + X$$

Measuring the charge of the leptons is not yet possible. However, the trajectories can be determined by Cherenkov-detectors.

Super-Kamiokande

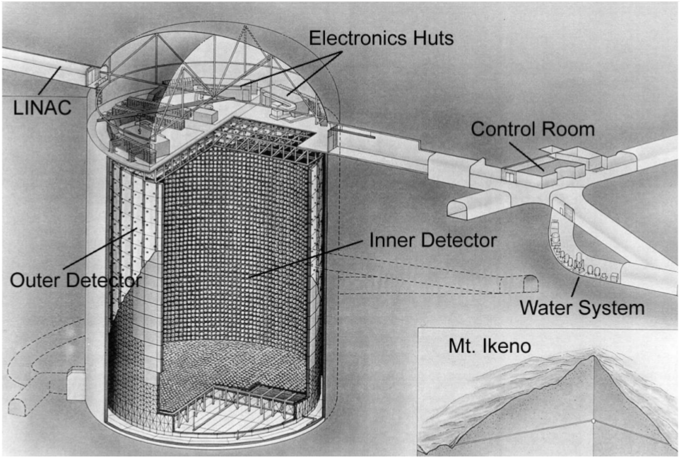


Figure : [Fukuda et al., 2003]

Zenith-Angle

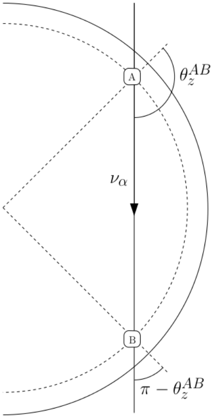


Figure : [Giunti and Kim, 2007b]

Different zenith angle means different L traveled through atmosphere and earth.

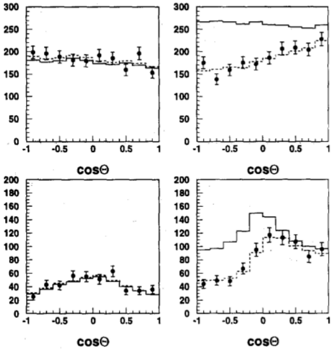


Figure : Zenith angle-dependent flux distribution. Top: sub-*GeV*, bottom: multi-*GeV*, left: *e*-like, right: μ-like. From [Kiełczewska, 2000].

Zenith-angle distribution

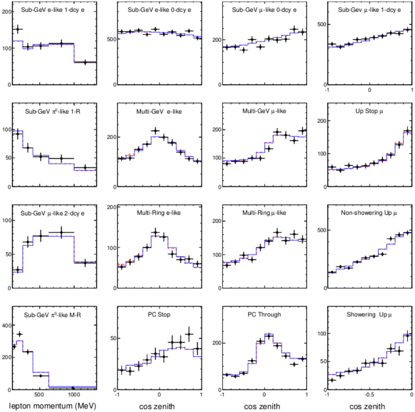


Figure : [Wendell et al., 2010].

Best fit for θ_{atm}:

$$\theta_{\mathrm{atm}} = 0.820 \pm 0.048$$

Best fit for $\Delta m^2_{\mathrm{atm}}$:

$$\Delta m^2_{atm} = 2.1 \cdot 10^{-3} eV^2$$

1. Historical Background
2. Theoretical Background
    - Neutrino mixing
    - Massive neutrinos
    - Why neutrinos are always said to be left handed
3. Discussion: theory
4. Experiments
    - Solar and atmospheric neutrinos
    - Reactor experiments
    - Accelerator experiments
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The reactor experiment

- $\overline{\nu_e}$ disappearance experiment
- Detection via inverse neutron-decay: $\overline{\nu_e} + p \rightarrow n + e^+$
- θ_{13} determined from *observed-to-predicted ratio of events*

Setup of the experiment:

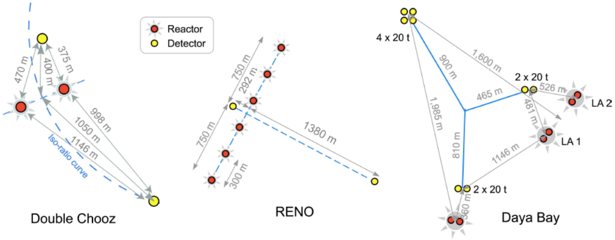

Figure : The nearby detectors measure the total flux, whereas the far away detectors measure a different relative flux due to oscillations [Mezzetto and Schwetz, 2010].

Survival probability[8]

$$\begin{aligned}
P_{\overline{\nu_e}\to\overline{\nu_e}} &= 1 - c_{13}^4 \sin^2 2\theta_{sol} \sin^2\left(1.27\frac{\Delta m_{sol}^2 L}{E}\right) \\
&\quad - c_{12}^2 \sin^2 2\theta_{13} \sin^2\left(1.27\frac{\Delta m_{13}^2 L}{E}\right) \\
&\quad - s_{12}^2 \sin^2 2\theta_{13} \sin^2\left(1.27\frac{\Delta m_{atm}^2 L}{E}\right) \\
&\approx 1 - \sin^2 2\theta_{13} \sin^2\left(1.27\frac{\Delta m_{atm}^2 L}{E}\right)
\end{aligned}$$

Here $\Delta m_{13}^2 \approx \Delta m_{atm}^2 \equiv \Delta m_{23}^2 = 2.4 \times 10^{-3}\,\mathrm{eV}^2$. Since also $c_{12}^2 + s_{12}^2 = 1$ the second and last line combine. Moreover, the first term can be dropped for small distances ($L < 5\,\mathrm{km}$) [Beringer et al., 2012].

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[8] [Guo et al., 2007, Abe et al., 2012b]

Daya-Bay results

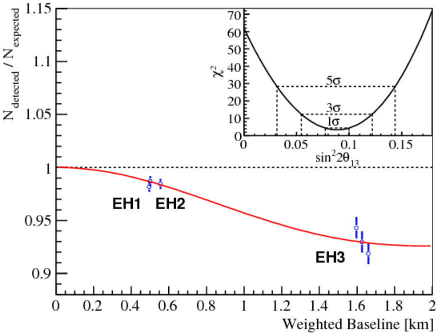


Figure : Disappearance of $\overline{\nu_e}$ at Daya Bay [Dwyer, 2013]

A simple calculation[9] to determine θ_{13}

Daya bay measured an anti-neutrino rate of:

$$\frac{\text{obs}}{\text{exp}} \approx 0.944$$

We have $L = 1.648\,\mathrm{km}$; $E_{\nu_{reactor}} \sim 10^{-3}\,\mathrm{GeV}$; $\Delta m^2_{atm} \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2$

$$\begin{aligned} P_{\overline{\nu_e} \to \overline{\nu_e}} &\approx 1 - \sin^2 2\theta_{13} \sin^2\left(1.27 \frac{\Delta m^2_{atm} L}{E}\right) \\ 0.944 &\approx 1 - \sin^2 2\theta_{13} \end{aligned}$$

$$\Rightarrow \boxed{\sin^2 2\theta_{13} \sim 0.1}$$

---

[9] After conducting a difficult experiment and doing statistical analysis.

Comparison of θ_{13} measurements

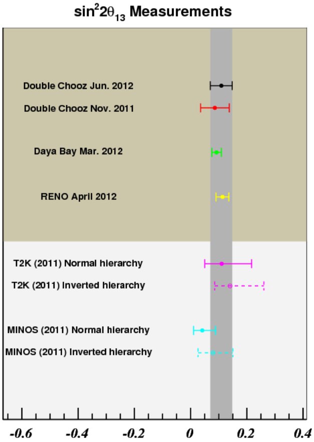


Figure : The dark region are reactor experiments, the light region accelerator experiments [Abe et al., 2012c]

The relevance of θ_{13}

The non-zero value of θ_{13} has some important consequences:

- There is a small part of ν_e in ν_3
- It allows for the possibility of CP violation in the lepton sector! (However, difficult to detect for smaller θ_{13})

Accelerator experiments

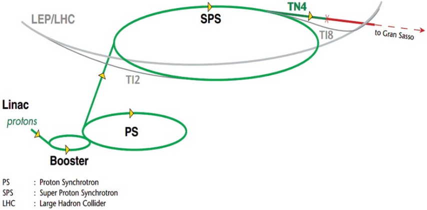
Accelerator experiments create a beam of μ neutrinos.
Advantages:

- Accurate determination of neutrino flux
- The parameters L and E can be set
  → Higher oscillation probability

Detectors measure the oscillation $P(\nu_\mu \to \nu_{e,\tau})$

Accelerator experiments:

- CNGS (2008-present)
- MINOS (2005-2013)
- T2K (2010-present)



Measuring mixing variables with accelerators

Accelerator experiments can set the value of L/E;

$\rightarrow$ *L/E* approximation of the transition probability for small L/E:

- $P(\nu_\mu \rightarrow \nu_\tau) = cos^2(\theta_{13}) sin^2(2\theta_{23}) sin^2(1.27\Delta m^2_{23} \frac{L}{E})$
- $P(\nu_\mu \rightarrow \nu_e) = sin^2(2\theta_{13}) sin^2(\theta_{23}) sin^2(1.27\Delta m^2_{23} \frac{L}{E})$

$\rightarrow$ *L/E* approximation of the transition probability for large L/E:

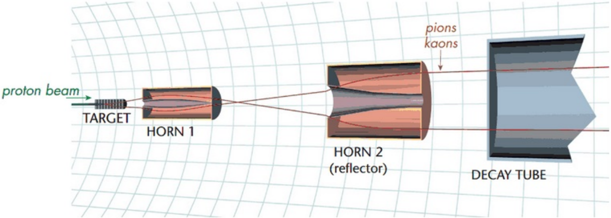
- $P(\nu_\mu \rightarrow \nu_e) = cos^2(\theta_{13}) sin^2(2\theta_{12}) sin^2(1.27\Delta m^2_{12} \frac{L}{E}) + sin^2(2\theta_{13})$

$P(\nu_\mu \rightarrow \nu_{e,\tau})$ is measured and the oscillation parameters are fitted onto the results.

CNGS

Accelerator beam at CERN

- SPS proton accelerator is used to collide protons
- Collision products (kaons and pions) are directed with magnetic lensing
- Collision products decay into e.g. muon neutrinos



CNGS detectors

During the propagation the ν_μ neutrinos oscillate and the appearance of ν_e and ν_τ are measured.

CNGS uses 2 main detectors:

- OPERA for the detection of ν_τ
  - $\nu_\tau + N \rightarrow \tau^- + X$
  - τ^- decay processes are detected
  - $\mathrm{P}(\nu_\mu \rightarrow \nu_\tau) = cos^2(\theta_{13}) sin^2(2\theta_{23}) sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$

- ICARUS for the detection of ν_e
  - ${}^{40}Ar + \nu_e \rightarrow^{40} K + e^-$
  - $\mathrm{P}(\nu_\mu \rightarrow \nu_e) = sin^2(2\theta_{13}) sin^2(\theta_{23}) sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$

[Kose, 2013]

Mass determination

Since the conventional model of neutrino oscillations require neutrinos to have mass, the mass of a neutrino will be determined with special relativity.

CNGS experiments measure the time difference between a photon and a neutrino.
$\delta t = \gamma t$ will be measured with OPERA and ICARUS
From gamma follows effective mass of the neutrino. [Adam et al., 2012]

$$m_{eff,\alpha} = \sum_i |U_{\alpha i}|^2 m_i$$

Time dilation

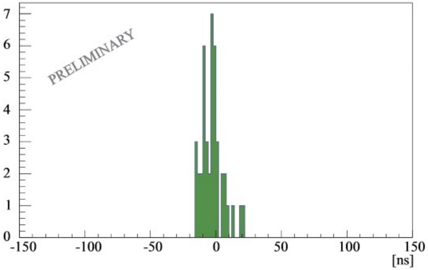


Figure : OPERA: $\delta t = -1.1^{+7.2}_{-4.8}\,\mathrm{ns}$

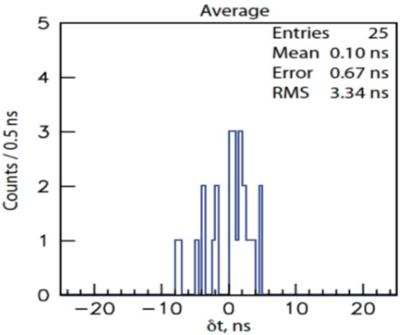


Figure : ICARUS $\delta t = 0.1 \pm 3.4\,\mathrm{ns}$

MINOS

Detector of the NuMI accelerator of Fermi lab
Special features:

- Can compare long base line with short base line
  $\rightarrow$ disappearance experiment for small L/E
  $\mathrm{P}(\nu_\mu \rightarrow \nu_\mu) = 1 - sin^2(2\theta_{23}) sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$
- Detectors are magnetized so that ν_μ and $\bar{\nu}_\mu$ can be separated
  $\nu_\mu(\bar{\nu}_\mu) + X \rightarrow \mu^-(\mu^+) + X'$

[Adamson et al., 2011b, Adamson et al., 2013]

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Detector of the NuMI accelerator of Fermi lab
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  $\nu_\mu(\bar{\nu}_\mu) + X \rightarrow \mu^-(\mu^+) + X'$

[Adamson et al., 2011b, Adamson et al., 2013]

If neutrinos and antineutrinos have different parameters, then this indicates that $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$.
This implies that CP is violated. $\rightarrow \delta_{CP} \neq 0$ [Abe et al., 2011]

MINOS

Detector of the NuMI accelerator of Fermi lab
Special features:

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  P($\nu_\mu \rightarrow \nu_\mu$)$= 1 - sin^2(2\theta_{23}) sin^2(1.27 \Delta m^2_{23} \frac{L}{E})$
- Detectors are magnetized so that ν_μ and $\bar{\nu}_\mu$ can be separated
  $\nu_\mu(\bar{\nu}_\mu) + X \rightarrow \mu^-(\mu^+) + X'$

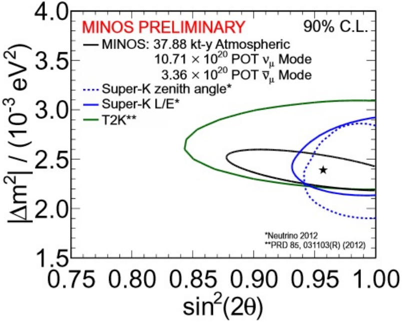
[Adamson et al., 2011b, Adamson et al., 2013]

If neutrinos and antineutrinos have different parameters, then this indicates that $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$.
This implies that CP is violated. $\rightarrow \delta_{CP} \neq 0$ [Abe et al., 2011]

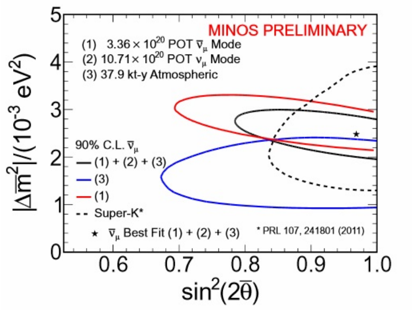
Other possibility: CPT violation.
→ Lorentz-violating neutrino oscillations [Greenberg, 2002]
→ The conventional neutrino oscillation model is wrong

MINOS neutrino vs anti- neutrino

neutrinos



anti-neutrinos



[Nich

Figure : $|\Delta m^2_{23}| = 2.39^{+0.09}_{-0.10} \cdot 10^{-3}\,\mathrm{eV}^2$; $sin^2(2\theta_{23}) = 0.96^{+0.04}_{-0.04}$

Figure : $|\Delta \bar{m}^2_{23}| = 2.48^{+0.22}_{-0.27} \cdot 10^{-3}\,\mathrm{eV}^2$; $sin^2(2\bar{\theta}_{23}) > 0.83$

MINOS: measuring θ_{13}

MINOS measures θ_{13} by performing an appearance experiment for $\nu_\mu \rightarrow \nu_e$
$P(\nu_\mu \rightarrow \nu_e) = sin^2(2\theta_{13})sin^2(\theta_{23})sin^2(1.27\Delta m^2_{23}\frac{L}{E})$

- $\theta_{23} = \frac{\pi}{4} \rightarrow sin^2(\theta_{23} = 0.5)$
- $|\Delta m_{32}|^2 = 2.32 \cdot 10^{-3} eV^2$

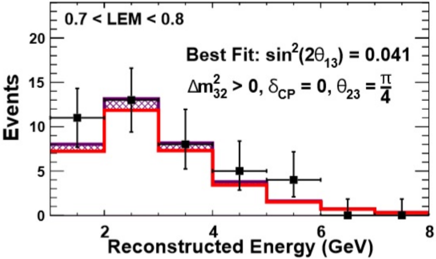


Figure : Best fit for the MINOS data: $sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$ [Adamson et al., 2011a].

CP-violation in MINOS

The mixing parameters change when CP-violation is added.

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$$

$$-4\sum_{k>j} \Re\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)$$

$$+2\sum_{k>j} \Im\left[U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}\right] \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

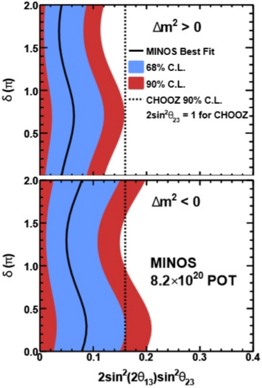


Figure : Allowed ranges for $2sin^2(2\theta_{13})sin^2(\theta_{23})$

[Adamson et al., 2011a]

T2K

T2K: Tokai to Kamioka

Appearance experiment $\nu_\mu \rightarrow \nu_e$

- $P(\nu_\mu \rightarrow \nu_e) = sin^2(2\theta_{13})sin^2(\theta_{23})sin^2(1.27\Delta m^2_{23}\frac{L}{E})$
- $\rightarrow sin^2(2\theta_{13}) = 0.104^{+0.060}_{-0.045}$ [Nakaya, 2013]

Disappearance expriments $\nu_\mu \rightarrow \nu_\mu$

- $P(\nu_\mu \rightarrow \nu_\mu)=$
  $1 - sin^2(2\theta_{23})sin^2(1.27\Delta m^2_{23}\frac{L}{E})$
- $\Delta m^2_{32} = 2.65 \pm 0.12 \cdot 10^{-3} eV^2$
- $sin^2(2\theta_{23}) = 0.98 \pm 0.05$

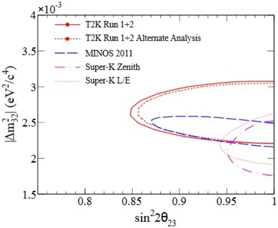


Figure : Parameter plot of T2K. [Abe et al., 2012a]

Overview of results: Mixing angles

Experiment	$sin^2(\theta_{12})$	$sin^2(2\theta_{13})$	$sin^2(2\theta_{23})$
IceCube			> 0.93
Super-Kamiokande	0.31 ± 0.01	$0.104^{+0.060}_{-0.045}$	0.98 ± 0.05
MINOS		$0.041^{+0.047}_{-0.031}$	> 0.83
Daya Bay		0.089 ± 0.015	
Double CHOOZE		0.109 ± 0.055	
RENO		0.113 ± 0.042	
Current Value (best fit)	0.32	0.096	0.95
Current value (3σ)	0.27-0.37	0.066-0.127	0.92-1

[Forero et al., 2012]

Overview of results: Mass

Experiments	Δm^2_{21}	$\|\Delta m^2_{32}\|$
MINOS		$2.41^{+0.09}_{-0.10} \cdot 10^{-3} eV^2$
IceCube		$2.3^{+0.6}_{-0.5} \cdot 10^{-3} eV^2$
Super-Kamiokande	$7.54 \pm 0.26 \cdot 10^{-5} eV^2$	$2.65 \pm 0.12 \cdot 10^{-3} eV^2$
Current value (best fit)	$7.62 \cdot 10^{-5} eV^2$	$2.55 \cdot 10^{-3} eV^2$
Current value (3σ)	$7.12 - 8.20 \cdot 10^{-5} eV^2$	$2.31 - 2.64 \cdot 10^{-3} eV^2$

[Forero et al., 2012]

LSND experiment

A SBL accelerator experiment used to measure $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearence events.

Has produced interesting results [Collaboration, 1996]:

- An excess of events in the lower energy spectrum.
- Which corresponds to an allowed region ΔM^2 of 0.2 - 2.0 eV^2
- And a possible region around $\Delta M^2 = 7$ eV^2.

LSND Results

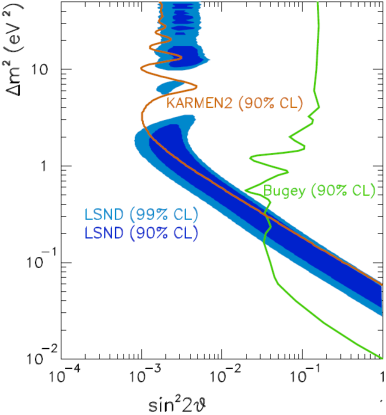


Figure : [Abazajian et al., 2012]

Implications of the LSND result

- The amount of Δm^2 found in the LSND experiment cannot be explained by the 3 known neutrino masses.
- The Large Electron Positron collider has only found three neutrinos with a mass smaller than one half of the mass of the Z boson
- So extra neutrinos do not couple to the weak force.

MiniBooNE

The interesting results of the LSND has led the MiniBooNE collaboration to try to further investigate $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- MiniBooNE had an L/E to match LSND.
- However E is an order of magnitude larger and thus the detector is further away as to produce independent results.
- MiniBoone is also devised to investigate $\nu_\mu \rightarrow \nu_e$.

MiniBooNE results

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ results [Collaboration, 2010]:

- In the low energy spectrum excesses have been found that could be in accordance with LSND.
- In the higher spectrum no excesses have been detected.

$\nu_\mu \rightarrow \nu_e$ results [Collaboration, 2008]

- In the lower region unexplainable excesses have been found.
- Higher energy again no excesses have been found.

The MiniBooNE results are however not conclusive.

Sterile Neutrino

A neutrino that does not couple to known SM forces.
How many are there?
Popular scenario:

- 3 + 1 sterile neutrino
- 3 + 2 sterile neutrinos

Recent global data analysis [Schwetz, 2013] shows that 3+2:

- has some favourable qualities concerning to LSND and MiniBooNE results
- (and 3+n in general) ultimately shows no major improvements over 3+1

Adding sterile neutrinos to the framework

New mass eigenstates ν_4,...,ν_n.
The index i runs from 1 to n in the mixing matrix $U_{\alpha i}$ and thus becomes a $3 \times (3 + n)$ matrix

- The amount of sterile neutrinos has an effect on the amount of parameters in $U_{\alpha i}$.
- Mixing angles θ_{kl} for $k, l > 3$ are not considered as they are not observable.

Outlook

Future experiments will tell us:

- Mass hierarchy and the absolute mass scale.
- Majorana or Dirac particle?
- CP-violation through neutrino oscillations?
- Are there sterile neutrinos?

Future experiments

KATRIN (Karlsruhe tritium neutrino experiment)

- will determine the absolute mass scale of neutrinos, by measuring the kinetic energy of electrons from tritium beta decay.
- A mass of 0.35 eV can be measured with 5σ significance

NOνA (NuMI off-axis ν_e appearance)

- Neutrinos from NuMI will pass 810 km through the Earth to a laboratory in Ash River, Minnesota
- Measures the oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$
- will determine the mass hierarchy and the CP-violating phase δ and measure θ_{13} more accurately (an order of magnitude better).

Both start in 2014.

Future experiments

Searches for neutrinoless double-beta decay, which can only happen if $\nu = \bar{\nu}$, thus showing that the neutrino is a Majorana:

The MAJORANA project [et al., a]

- Uses germanium crystals enriched in Ge-76, most favourable isotope for $0\nu\beta\beta$, the lifetime of Ge-76 is greater than 2×10^{25} years.

SuperNEMO (Neutrino Ettore Majorana Observatory)

- Uses different isotopes, same technique

Future experiments

MINOS+ [et al., b]

- MINOS upgrade, started ∼2 months ago
- Will measure Δm^2_{23}, θ_{23}, $\Delta \bar{m}^2_{23}$ and $\bar{\theta}_{23}$ more accurately
- Will search for sterile neutrinos in the $3 + 1$ model

LSND reloaded [Sanjib K. Agarwalla,]

- Repeat LSND with Super-Kamiokande detector
- Will be able to test the LSND and MiniBooNE claims with 5σ significance.
- Still a proposal

The future

- There are many more experiments proposed /planned.
- In the next decade the mass hierarchy and absolute mass scale of the neutrinos will be found
- Moreover, maybe we will discover CP-violation in the lepton sector and the first Majorana particle
- And more lies ahead in coming decade

Thank You!

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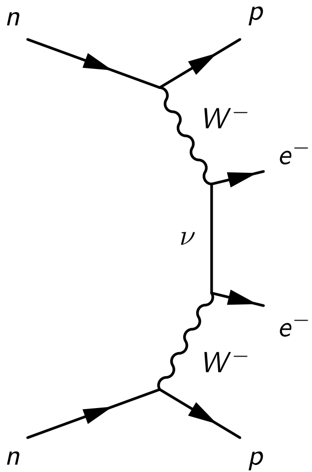
Neutrinoless 2β – *decay*

If observed:

- Would be a proof that neutrinos are majorana particles
- Lepton number violation



Three-neutrino bilarge mixing

In this case the mixing matrix is real, and as a consequence there is no CP or T violation. It occurs when $\theta_{13} = 0$.

$$U^D = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23} & -c_{12}c_{23} & c_{23} \end{pmatrix}$$