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Past decades  Experimental verification of neutrino oscillations

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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 $\nu \leftrightarrow \bar{\nu}$ transition may occur in analogy with $K^0 \leftrightarrow \bar{K}^0$ (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 $\nu_e$ were tested, of the expected flux of $\nu_e$ 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.
3 neutrino flavors, $\nu_e$, $\nu_\mu$, and $\nu_\tau$ are known, mixing of the 3 generations have been seen in many experiments.

Definition of flavor: $\nu_\alpha$ is the particle which couples to $\ell_\alpha$ through weak interaction.

flavor eigenstates, but mixed states of mass eigenstates (In SM flavor eigenstate = mass eigenstate).
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:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \quad (\alpha = e, \mu, \tau)$$
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 $3 \times 3$ matrix this leads to 3 angles and 1 phase.
A 2 × 2 unitary matrix can be written as matrix which depends on 3 phases $\omega_1$, $\omega_2$ and $\eta$ and 1 angle $\theta$

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

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

Four fields are present, flavor eigenstates $\nu_e$, $\nu_\mu$ and mass eigenstates $\nu_1$, $\nu_2$, 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:

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu
\end{pmatrix} =
\begin{pmatrix}
\cos \theta & \sin \theta \\
- \sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]
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 \(s_{ab} \equiv \sin \theta_{ab}\)

\(\theta_{ab}\) are mixing angles

\(\delta\) is called CP-violating phase or Dirac phase.

\(^3\)A derivation can be found in [Giunti and Kim, 2007a].
If neutrinos are Majorana particles:

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

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 $P_{\nu_\alpha \rightarrow \nu_\beta}(t)$

- The mass eigenstates $|\nu_k\rangle$ are eigenstates of $H$, with energy $E_k = \sqrt{p^2 + m^2}$
- 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 $A_{\nu_\alpha \rightarrow \nu_\beta}(t)$ is:

$$A_{\nu_\alpha \rightarrow \nu_\beta}(t) = \langle \nu_\beta | \nu_\alpha(t) \rangle = \sum_\beta \left( \sum_k U_{\alpha k}^* e^{-iE_k t} U_{\beta k} \right) \langle \nu_\beta | \nu_\alpha \rangle = \sum_k U_{\alpha k}^* U_{\beta k} e^{-iE_k t}$$
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 $\Delta m^2_{kj} \equiv \Delta m^2_k - \Delta m^2_j$
We can write the oscillation probability also in the form

\[ P_{\nu_\alpha \rightarrow \nu_\beta}(t) = \delta_{\alpha\beta} - 4 \sum_{k>j} \text{Re} \left[ U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^* \right] \sin^2 \left( \frac{\Delta m_{kj}^2 L}{4E} \right) \]

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

Assuming CPT invariance:
For antineutrinos we have that \( P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta}(t) \) is the same up to a minus sign in third term.
A CP transformation interchanges neutrinos with negative helicity and antineutrinos with positive helicity, so $\nu_\alpha \rightarrow \nu_\beta$ becomes $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$.

This CP transformation changes $U \leftrightarrow U^*$.

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 $A_{\alpha\beta}^{CP}(L, E)$:
Oscillations and CP-violation

\[ A_{\alpha\beta}^{CP}(L, E) = 4 \sum_{k>j} \text{Im} \left[ U_{\alpha k}^{*} U_{\beta k} U_{\alpha j} U_{\beta j}^{*} \right] \sin \left( \frac{\Delta m_{kj}^2 L}{2E} \right) \]

- \( U_{\alpha k}^{*} U_{\beta k} U_{\alpha j} U_{\beta j}^{*} \) does not depend on the Majorana phases, so they do not influence the oscillations;
- it does only depend on \( \delta \), 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 $\Delta m^2_{kj}$.

- 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.

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

- We can measure $\Delta m^2_{kj}$, however not the absolute values of the masses.
- The mass hierarchy of neutrinos is unknown.
- Depends on the sign of $\Delta m^2_{13}$ 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 $\Delta m^2_{12} < \Delta m^2_{23}$. 
Neutrino squared-mass spectrum

\[ \Delta m_{12}^2 \equiv \Delta m_{\odot}^2 \simeq 8.0 \times 10^{-5} \text{eV}^2, \quad \Delta m_{23}^2 \equiv \Delta m_{\text{atm}}^2 \simeq 2.4 \times 10^{-3} \text{eV}^2 \]

\( \sin^2 \theta_{13} \quad \text{Bounded by reactor exps. with } L \sim 1 \text{ km} \)

From max. atm. mixing, \( \nu_3 = \frac{\nu_\mu + \nu_\tau}{\sqrt{2}} \)

\( \Delta m_{\text{atm}}^2 \left\{ \begin{array}{l} \text{From } \nu_\mu \text{ (Up) oscillate but } \nu_\mu \text{ (Down) don't} \\ \text{In LMA–MSW, } P_{\text{sol}}(\nu_e \rightarrow \nu_e) = \nu_e \text{ fraction of } \nu_2 \end{array} \right\} \)

\( \Delta m_{\text{sol}}^2 \rightarrow \text{From distortion of } \nu_e \text{ (solar) and } \nu_e \text{ (reactor) spectra} \)

\( \left\{ \begin{array}{l} \text{From max. atm. mixing, } \nu_1 + \nu_2 \\ \text{includes } (\nu_\mu - \nu_\tau) / \sqrt{2} \end{array} \right\} \)

\[ |U_{ei}|^2 \quad |U_{\mu i}|^2 \quad |U_{\tau i}|^2 \]

Figure: [Kayser, 2005]
Normal and inverted hierarchy

Figure: citeGouvea2005
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).
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Higgs-lepton Lagrangian

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

\[
L_{L,\alpha} = \begin{pmatrix} \nu_{\alpha,L} \\ \alpha_L \end{pmatrix} \quad \text{where } \alpha = e, \mu, \tau
\]

\[
\ell_{R,\alpha} = \alpha_R
\]

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

So no neutrino mass:

\[
\mathcal{L}_{H,L} = -\sum_\alpha \frac{y_\alpha^\ell v}{\sqrt{2}} \ell_{L,\alpha} \ell_{R,\alpha} - \sum_\alpha \frac{y_\alpha^\ell}{\sqrt{2}} \ell_{L,\alpha} \ell_{R,\alpha} H + \text{h.c.}
\]
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 $\Rightarrow$ sterile

This leads to an additional term in the Lagrangian:

$$\mathcal{L}_{H, L} = - \left( \frac{\nu + H}{\sqrt{2}} \right) \left( \sum_{\alpha=e,\mu,\tau} y_{\alpha L, \alpha L, \alpha L} + \sum_{k=1,2,3} y_{k L, k L, k L} + h.c \right)$$

$$\Rightarrow m_k = \frac{y_{k L} v}{\sqrt{2}}$$

\(^4\)In principle, there is no objection to only having 1 right-handed neutrino.
Neutrino flavor mixing

The above scenario allows for neutrino flavor mixing:

\[ \nu_L = U n_L \text{ where } \nu_L = \begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} \text{ and } n_L = \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} \]

However, it does not:

- allow for mixing between neutrinos and sterile neutrinos \( (\nu_R) \rightarrow \) necessary?
- explain the small mass of neutrinos (i.e. the small value of \( y_n^k \))

Possible solution: See-saw mechanism
Majorana Neutrinos

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

- $\psi = C\psi^T$ or $\psi = \psi^C$

This is satisfied if one replaces $\psi_{R/L}$ by $\psi_{L/R}^C$ (or $C\psi_{L/R}^T$)$^5$

The Majorana Lagrangian mass terms then becomes:

$$\mathcal{L}_L^{mass} = -\frac{1}{2} m_L \bar{\nu}_L \nu_L + h.c$$

$$\mathcal{L}_R^{mass} = -\frac{1}{2} m_R \bar{\nu}_R \nu_R + h.c$$

and the Dirac Lagrangian as defined above:

$$\mathcal{L}_D^{mass} = -m_D \bar{\nu}_R \nu_L + h.c$$

$^5$Require the field equations to be identical.
The most general Dirac-Majorana Lagrangian for one generation:

\[
\mathcal{L}^{D+M}_{\text{mass}} = \mathcal{L}^{D}_{\text{mass}} + \mathcal{L}^{L}_{\text{mass}} + \mathcal{L}^{R}_{\text{mass}} \\
= -\frac{1}{2} m_D \overline{\nu}_R \nu_L - \frac{1}{2} m_L \overline{\nu}_L \nu_L - \frac{1}{2} m_R \overline{\nu}_R \nu_R + \text{h.c.} \\
= -\frac{1}{2} \begin{pmatrix} \overline{\nu}_L & \overline{\nu}_R \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + \text{h.c.}
\]

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
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 $\theta$ is the mixing angle and $\lambda$ a CP-violating phase.

In general:

$$\tan 2\theta = \frac{2m_D}{m_R - \Re[m_L]}$$
Introducing this unitary matrix:

\[
\mathcal{L}_{\text{mass}}^{D+M} = -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + \text{h.c.}
\]

\[
= -\frac{1}{2} \bar{N}_L^c MN_L + \text{h.c}
\]

\[
= -\frac{1}{2} \bar{N}_L^c UU^\dagger MUU^\dagger N_L + \text{h.c}
\]

\[
= -\frac{1}{2} \sum_{k=1,2} m_k \bar{\nu}_k^c \nu_k L + \text{h.c.}
\]

With \( \nu_k = \nu_{kL} + \nu_{kL}^C \)
See-Saw mechanism

\[ m_D \ll m_R \text{ and } m_L = 0 \implies M = \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \]

Eigenvalues are: 
\[ m_1 \approx \frac{m_D^2}{m_R} ; \]
\[ m_2 \approx m_R \]

\[ \Rightarrow \] a very light neutrino and a massive sterile neutrino are created

Moreover, small mixing:

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

\[ ^{[\text{Mulders, 2012, Giunti and Kim, 2007a}]} \]
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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: $\pi^-$ has spin zero, $\mu^-$ experimentally turns out to always be right-handed ($h = +1$) [Griffiths, 2008].
Chirality: a different definition of handedness

**Definition:** eigenvalue of $\gamma^5$

For Weyl spinors (eigenfunctions of $\gamma^5$):

\[
\begin{align*}
\gamma^5 \psi_R &= +\psi_R \\
\gamma^5 \psi_L &= -\psi_L
\end{align*}
\]

$\Rightarrow$ neutrinos: again called right- and left-handed

\[
\begin{align*}
\gamma^5 \overline{\psi}_R &= -\overline{\psi}_R \\
\gamma^5 \overline{\psi}_L &= +\overline{\psi}_L
\end{align*}
\]

$\Rightarrow$ anti neutrinos: left- and right-handed respectively

Chirality is Lorentz invariant!
Relation between chirality and helicity for $m = 0$

Field equations:

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

For massless fields one can show that:

$$\hat{h}\psi_R = +\psi_R$$
$$\hat{h}\psi_L = -\psi_L$$

$$\Rightarrow$$ for $m = 0$ chirality $\leftrightarrow$ helicity

As you would expect, for $m = 0$ helicity is also Lorentz invariant!
Only left-chiral neutrinos

Let us only consider the $\mu$ neutrinos, we have in the simplest picture:

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

Recall that $N_L = U n_L$!!

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

\[ d \quad Z \quad \bar{u} \]

\[ \bar{\nu}_{mL} \quad \mu^- \]

Since we have \( \nu_L = U_{11}\nu_{1L} + U_{12}\nu_{2L} \)
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Essentially two kinds of oscillations experiments

- Appearance measurements $\rightarrow$ measure transition probability
- Disappearance measurements $\rightarrow$ measure survival probability

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

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

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<th>$E$</th>
<th>$\Delta m^2$ sensitivity</th>
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<td>Reactor SBL</td>
<td>$\sim 10,\text{m}$</td>
<td>$\sim 1,\text{MeV}$</td>
<td>$\sim 0.1,\text{eV}^2$</td>
</tr>
<tr>
<td>Accelerator SBL (Pion DIF)</td>
<td>$\sim 1,\text{km}$</td>
<td>$\gtrsim 1,\text{GeV}$</td>
<td>$\gtrsim 1,\text{eV}^2$</td>
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<tr>
<td>Accelerator SBL (Muon DAR)</td>
<td>$\sim 10,\text{m}$</td>
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</tr>
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<td>$\sim 10^{-3},\text{eV}^2$</td>
</tr>
<tr>
<td>Accelerator LBL</td>
<td>$\sim 10^3,\text{km}$</td>
<td>$\gtrsim 1,\text{GeV}$</td>
<td>$\gtrsim 10^{-3},\text{eV}^2$</td>
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<tr>
<td>Reactor VLB</td>
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<td>$\sim 1,\text{MeV}$</td>
<td>$\sim 10^{-5},\text{eV}^2$</td>
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<tr>
<td>Accelerator VLB</td>
<td>$\sim 10^4,\text{km}$</td>
<td>$\gtrsim 1,\text{GeV}$</td>
<td>$\gtrsim 10^{-4},\text{eV}^2$</td>
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<tr>
<td>SOL</td>
<td>$\sim 10^{11},\text{km}$</td>
<td>$0.2–15,\text{MeV}$</td>
<td>$\sim 10^{-12},\text{eV}^2$</td>
</tr>
</tbody>
</table>

**Figure:** [Giunti and Kim, 2007a]
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
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6. References
Solar Neutrinos

Both from [Giunti and Kim, 2007b]

\[
\begin{align*}
(p) & \quad p + p \rightarrow ^2 \text{H} + e^+ + \nu_e \\
(pei) & \quad p + e^- + p \rightarrow ^2 \text{H} + \nu_e \\
(p) & \quad ^3 \text{H} + p \rightarrow ^3 \text{He} + \gamma \\
(hep) & \quad ^3 \text{He} + p \rightarrow ^4 \text{He} + e^+ + \nu_e \\
(7\text{Be}) & \quad ^7 \text{Be} + e^- \rightarrow ^7 \text{Li} + \nu_e \\
(ppI) & \quad ^7 \text{Li} + p \rightarrow 2^4 \text{He} \\
(ppII) & \quad ^7 \text{Be} + p \rightarrow ^8 \text{B} + \gamma \\
(hep) & \quad ^8 \text{B} \rightarrow ^8 \text{Be}^* + e^+ + \nu_e \\
(ppIII) & \quad ^8 \text{Be}^* \rightarrow 2^4 \text{He} \\
(15\text{O}) & \quad ^{15} \text{O} + ^{12} \text{C} \rightarrow ^{13} \text{N} + e^+ + \nu_e \\
(13\text{N}) & \quad ^{13} \text{N} \rightarrow ^{13} \text{C} + e^+ + \nu_e \\
(13\text{C}) & \quad ^{13} \text{C} + p \rightarrow ^{14} \text{N} + \gamma \\
(14\text{N}) & \quad ^{14} \text{N} + p \rightarrow ^{15} \text{O} + \gamma \\
(17\text{O}) & \quad ^{17} \text{O} + ^{16} \text{O} \rightarrow ^{15} \text{N} + e^+ + \nu_e \\
(15\text{N}) & \quad ^{15} \text{N} + p \rightarrow ^{16} \text{O} + \gamma \\
(16\text{O}) & \quad ^{16} \text{O} + p \rightarrow ^{17} \text{F} + \gamma \\
(17\text{F}) & \quad ^{17} \text{F} \rightarrow ^{17} \text{O} + e^+ + \nu_e
\end{align*}
\]
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**: $\nu_\alpha + e^- \rightarrow \nu_\alpha + e^- \left( \sigma_{\nu_e} \approx 6\sigma_{\nu_{\mu,\tau}} \right)$
Homestake experiment used $^{37}\text{Cl}$ solved in water for CC-reaction:

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

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

Figure: [Davis, 1994]

$1 \text{SNU} = 10^{-36} \nu$ captures per target atom per second
Neutral current, Charged current and electron-scattering are measured.

Isotropic $\gamma$’s from NC neutron reactions are detected.

$E_\gamma$ well above background.
SNO-results

Figure: From [Giunti and Kim, 2007b]

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

The solar mixing parameters are (best fit):

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

Figure: From [Ahmed et al., 2004]
Matter oscillations

Our distance to the sun ($L$) varies:

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

Oscillations in Matter

- In matter, $\nu_e$ can interact with $e^-$ via CC.
- All $\nu$ can interact via NC.
- Extra potential energy terms in Hamiltonian:

$$H_M = H_{\text{vac}} + V_W \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} + V_Z \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

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
$\Delta m^2$ and $\theta$ replaced by effective $\Delta m_m^2$ and $\theta_m^7$:

\[
\Delta m_m^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}
\]

\[
\sin^2 2\theta_m \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}
\]

\[
x \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2}
\]

$\Rightarrow$ Matter factor proportional to $E$ and $n_e$.

---

$^7$For a detailed derivation, see [Giunti and Kim, 2007b] or [Kayser, 2005]
For $^8B\nu_e$ in the centre of the sun, the $V_C$ term in the Hamiltonian dominates.

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

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

Propagating to the edge of the sun, the neutrino remains eigenstate of total $H_M$, and thus emerges as upper eigenstate $|\nu_2\rangle$ of $H_{\text{vac}}$ from the sun.

From there, it propagates as a normal $|\nu_2\rangle$ from the sun without oscillating.

The probability that it interacts as $\nu_e$ on earth is thus proportional to $|U_{e2}|^2 = \theta_{sol} \approx \frac{1}{3}$, 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 $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$

Expected flux ratio:

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

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

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

![Diagram of Super-Kamiokande](image)

**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: $\mu$-like. From [Kiełczewska, 2000].
Best fit for $\theta_{\text{atm}}$:
\[ \theta_{\text{atm}} = 0.820 \pm 0.048 \]

Best fit for $\Delta m_{\text{atm}}^2$:
\[ \Delta m_{\text{atm}}^2 = 2.1 \cdot 10^{-3} \text{eV}^2 \]

Figure: [Wendell et al., 2010].
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The reactor experiment

- $\overline{\nu_e}$ disappearance experiment
- Detection via inverse neutron-decay: $\overline{\nu_e} + p \rightarrow n + e^+$
- $\theta_{13}$ 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].
$P_{\nu_e \rightarrow \nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{\text{sol}} \sin^2 \left(1.27 \frac{\Delta m^2_{\text{sol}} L}{E} \right)$

$- c_{12}^2 \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m^2_{13} L}{E} \right)$

$- s_{12}^2 \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m^2_{\text{atm}} L}{E} \right)$

$\approx 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m^2_{\text{atm}} L}{E} \right)$

Here $\Delta m^2_{13} \approx \Delta m^2_{\text{atm}} \equiv \Delta m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2$. 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 ($L < 5 \text{km}$) [Beringer et al., 2012].

---

[Guo et al., 2007, Abe et al., 2012b]
Figure: Disappearance of $\bar{\nu}_e$ at Daya Bay [Dwyer, 2013]
A simple calculation\textsuperscript{9} to determine $\theta_{13}$

Daya bay measured an anti-neutrino rate of:

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

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

$$P_{\bar{\nu}_{e} \rightarrow \nu_{e}} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27 \frac{\Delta m_{\text{atm}}^{2}L}{E}\right)$$

$$0.944 \approx 1 - \sin^2 2\theta_{13}$$

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

\textsuperscript{9}After conducting a difficult experiment and doing statistical analysis.
Comparison of $\theta_{13}$ measurements

Figure: The dark region are reactor experiments, the light region accelerator experiments [Abe et al., 2012c]
The relevance of $\theta_{13}$

The non-zero value of $\theta_{13}$ has some important consequences:

- There is a small part of $\nu_e$ in $\nu_3$
- It allows for the possibility of CP violation in the lepton sector! (However, difficult to detect for smaller $\theta_{13}$)
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Accelerator experiments create a beam of $\mu$ neutrinos. Advantages:

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

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

Accelerator experiments:
- CNGS (2008-present)
- MINOS (2005-2013)
- T2K (2010-present)
Accelerator experiments can set the value of $L/E$;

→ $L/E$ approximation of the transition probability for small $L/E$:

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

→ $L/E$ 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.
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
During the propagation the $\nu_\mu$ neutrinos oscillate and the appearance of $\nu_e$ and $\nu_\tau$ are measured.

CNGS uses 2 main detectors:

- **OPERA** for the detection of $\nu_\tau$
  - $\nu_\tau + N \rightarrow \tau^- + X$
  - $\tau^-$ decay processes are detected
  - $P(\nu_\mu \rightarrow \nu_\tau) = \cos^2(\theta_{13})\sin^2(2\theta_{23})\sin^2(1.27\Delta m_{23}^2 L)$

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

[Kose, 2013]
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]

\[ m_{\text{eff},\alpha} = \sum_i |U_{\alpha i}|^2 m_i \]
Time dilation

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

Figure: ICARUS $\delta t = 0.1 \pm 3.4 \text{ ns}$
MINOS

Detector of the NuMI accelerator of Fermi lab
Special features:

- Can compare long base line with short base line → disappearance experiment for small L/E
  \[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m_{23}^2 \frac{L}{E}) \]

- Detectors are magnetized so that \( \nu_\mu \) 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]
Detector of the NuMI accelerator of Fermi lab

Special features:

- Can compare long base line with short base line
  → disappearance experiment for small L/E
  \[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2(1.27 \Delta m_{23}^2 \frac{L}{E}) \]

- Detectors are magnetized so that \( \nu_\mu \) and \( \overline{\nu}_\mu \) can be separated
  \[ \nu_\mu (\overline{\nu}_\mu) + X \rightarrow \mu^- (\mu^+) + X' \]

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

If neutrinos and antineutrinos have different parameters, then this indicates that
\[ P(\nu_\mu \rightarrow \nu_\mu) \neq P(\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu). \]
This implies that CP is violated. → \( \delta_{CP} \neq 0 \) [Abe et al., 2011]
Detector of the NuMI accelerator of Fermi lab

Special features:

- Can compare long base line with short base line → disappearance experiment for small $L/E$
  \[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m_{23}^2 \frac{L}{E}) \]

- Detectors are magnetized so that $\nu_\mu$ 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. → $\delta_{CP} \neq 0$ [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

\[ |\Delta m^2_{23}| = 2.39^{+0.09}_{-0.10} \times 10^{-3} \text{ eV}^2; \]
\[ \sin^2(2\theta_{23}) = 0.96^{+0.04}_{-0.04} \]

\[ |\Delta \bar{m}^2_{23}| = 2.48^{+0.22}_{-0.27} \times 10^{-3} \text{ eV}^2; \]
\[ \sin^2(2\bar{\theta}_{23}) > 0.83 \]
MINOS: measuring $\theta_{13}$

MINOS measures $\theta_{13}$ by performing an appearance experiment for $\nu_\mu \rightarrow \nu_e$

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

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

**Figure**: Best fit for the MINOS data: $\sin^2(2\theta_{13}) = 0.041^{+0.047}_{-0.031}$ [Adamson et al., 2011a].
The mixing parameters change when CP-violation is added.

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} \]

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

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

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

[Adamson et al., 2011a]
T2K: Tokai to Kamioka

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

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

Disappearance experiments $\nu_\mu \rightarrow \nu_\mu$

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

Figure: Parameter plot of T2K. [Abe et al., 2012a]
Overview of results: Mixing angles

<table>
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<tr>
<th>Experiment</th>
<th>$\sin^2(\theta_{12})$</th>
<th>$\sin^2(2\theta_{13})$</th>
<th>$\sin^2(2\theta_{23})$</th>
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<tr>
<td>Super-Kamiokande</td>
<td>0.31 ± 0.01</td>
<td>0.104$^{+0.060}_{-0.045}$</td>
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<td>Daya Bay</td>
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<td>Current value (3$\sigma$)</td>
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<td>0.066-0.127</td>
<td>0.92-1</td>
</tr>
</tbody>
</table>

[Forero et al., 2012]
## Overview of results: Mass

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

[Forero et al., 2012]
LSND experiment

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

Has produced interesting results [Collaboration, 1996]:

- An excess of events in the lower energy spectrum.
- Which corresponds to an allowed region $\Delta M^2$ of 0.2 - 2.0 eV$^2$
- And a possible region around $\Delta M^2 = 7$ eV$^2$. 
Figure: [Abazajian et al., 2012]
Implications of the LSND result

- The amount of $\Delta m^2$ 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.
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.
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 $\nu_4, \ldots, \nu_n$.
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 $\theta_{kl}$ for $k, l > 3$ are not considered as they are not observable.
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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?
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 $5\sigma$ significance

NO$\nu$A (NuMI off-axis $\nu_e$ appearance)
- Neutrinos from NuMI will pass 810 km through the Earth to a laboratory in Ash River, Minnesota
- Measures the oscillations $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- will determine the mass hierarchy and the CP-violating phase $\delta$ and measure $\theta_{13}$ 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 \textsc{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 $2 \times 10^{25}$ years.

SuperNEMO (Neutrino Ettore Majorana Observatory)

- Uses different isotopes, same technique
Future experiments

MINOS+  [et al., b]
- MINOS upgrade, started \( \sim \) 2 months ago
- Will measure \( \Delta m_{23}^2, \theta_{23}, \Delta \bar{m}_{23}^2 \) 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 \( 5\sigma \) 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!
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

5 Outlook

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Neutrinoless $2\beta - decay$

If observed:

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

\[ n \rightarrow \nu \rightarrow p + e^- + e^- \]

\[ n \rightarrow W^- \rightarrow p + e^- + e^- \]
In this case the mixing matrix is real, and as a consequence there is no CP or T violation. It occurs when $\theta_{13} = 0$.

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