Chapter 1

Theory of neutrino physics

Just give a short overview of the historical context, but mainly focusing on the actual description of the neutrino theory, mostly stating the fact rather than giving a large background 1.neutrino interactions (neutrinos in the SM) - detection of neutrinos? 2.neutrino oscillations (including possible sterile oscillation) - maybe current status? 3.neutrino masses (theoretical prediction for their origins and their measurements)

I should discuss everything that is even briefly mentioned in the neutrino magnetic moment theory section.

- Dirac vs Majorana neutrinos
- Neutrino masses
- Neutrino interactions with electrons and nuclei
- Neutrino oscillations and their implications

The story:

1. Brief history up to neutrinos being in the SM
2. Description of neutrinos in the SM
3. Interactions of neutrinos and their detection
4. Production of neutrinos
5. Solar and atmospheric neutrino anomalies and neutrino oscillations
6. Detail of neutrino oscillations for three flavours
7. Current state of neutrino oscillation measurements
8. Mass ordering, octant, delta CP

9. Neutrino masses - generation and measurements

10. Dirac V Majorana neutrinos

Neutrinos were first introduced [1, 2] as very light, half-spin electrically neutral particles with possible magnetic moments [3]. Being a crucial part of the successful theory of weak interactions [4, 5], neutrinos solidified their important in particle physics even before they were first experimentally detected. Neutrinos eventually developed into the two-component left-handed chiral fields $\nu_{\alpha L}$, with three generations $\alpha = e, \mu, \tau$ denoting the three know neutrino flavours [6–8], with no mass or magnetic moment, we use today in the Standard Model (SM) of particle physics [9–11]. They form weak isospin doublets together with their associated left handed charged lepton fields and unlike the charged leptons, neutrinos do not have an associated right handed singlet in the SM. Therefore, they do not obtain their masses via the Higgs mechanism through the Yukawa coupling, which requires the both left handed and right handed fields, therefore there is no mass term in the SM lagrangian [12]. The neutrino interaction terms of the SM lagrangian can be separated into two, Charged current (CC) or Neutral Current (NC) based on the massive gauge field they interact with. They can be written as

$$\mathcal{L}_{\text{CC}}^{\text{SM}} = -\frac{g_w}{2\sqrt{2}} j_W^\mu W_\mu + \text{h.c.}, \quad \mathcal{L}_{\text{NC}}^{\text{SM}} = -\frac{g_w}{2\cos(\theta_W)} j_Z^\mu Z_\mu, \tag{1.1}$$

where g_w is the weak coupling constant, θ_W is the Weinberg angle, W_μ and Z_μ are the 4-component vector gauge fields describing the $W^\pm$ and Z^0 weak bosons and j_W^μ and j_Z^μ are the weak currents. The currents are expressed as as

$$j_W^\mu = 2 \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L} \gamma^\mu \alpha_L, \tag{1.2}$$

$$j_Z^\mu = 2 \sum_{\alpha=e,\mu,\tau} g_L^\nu \overline{\nu}_{\alpha L} \gamma^\mu \nu_{\alpha L}, \tag{1.3}$$

where $\gamma^\mu, \mu = 0, 1, 2, 3$, are the four Dirac gamma matrices, α_R is the right handed chiral field for the charged lepton α and g_L^ν is the coupling term.

TO DO: *Need to actually properly mention that there are three fermion generations*

The interaction lagrangian described in Eq. 1.1 describes two possible vertices for the neutrino interaction, as shown on Fig. 1.1.

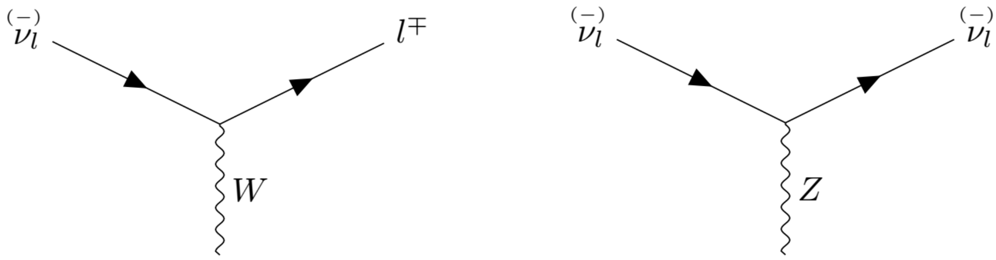

Figure 1.1: Neutrino interaction vertices in the SM via the weak charged currents (left) and neutral currents (right).

1.1 Neutrino Production

The main neutrino sources [12] are the β^- decay, which is essentially a neutron decay, happening in radioactive materials, or nuclear reactors, and can be described as

$$n \rightarrow p + e^- + \overline{\nu}_e. \tag{1.4}$$

The source of neutrinos from nuclear reactor was the first artificial source of neutrinos which brought increase of neutrino rate of about 10^7, as well as higher neutrino energies and enabled the first detection of neutrinos [13] Similarly is the β^+ decay

$$p \rightarrow n + e^+ + \nu_e \tag{1.5}$$

or the electron capture

$$p + e^- \rightarrow n + \nu_e, \tag{1.6}$$

which occurs in the stars and for Earth especially in the Sun. Source of ν_μ is especially pion, muon and kaon decay, occurring in the atmosphere when the cosmic ray protons interact with the nuclei in the atmosphere and the accelerators

$$p + X \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu\,(\overline{\nu}_\mu) \tag{1.7}$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_\mu\,(\overline{\nu}_\mu) + \nu_e\,(\overline{\nu}_e) \tag{1.8}$$

Notice that if all muons decay by the time they reach Earth's surface, then there should be almost exactly 2:1 ratio of $\nu_\mu : \nu_e$ for atmospheric neutrinos. This ratio increases with the neutrino energy as more energetic muons have lower chance of decaying before reaching the surface. Also $\frac{\phi_{\nu_\mu}}{\phi_{\overline{\nu}_\mu}} \approx 1$ This is also used in the modern accelerator based source of neutrinos which have accelerated protons strike a fixed target [14][15].

For supernovas its partly electron capture but 90% through thermal pair production

$$e^- + e^+ \to \nu_\alpha + \overline{\nu}_\alpha, \alpha = e, \mu, \tau \tag{1.9}$$

There is also cosmic neutrino background that decoupled from the rest of matter shortly after the Big Bang.

1.2 Neutrino Interactions

Inversely, the detection of neutrinos is usually done by reverting the above mentioned processes. The discussion of neutrino interactions is in [16]

For example for the $\overline{\nu}_e$ we can use the so-called inverse beta decay

$$\overline{\nu}_e + p \to n + e^+ \tag{1.10}$$

was used for the first detection of neutrinos by Cowan and Reines [17, 18]. This is currently used in the reactor neutrino experiments COMMENT: *Should I mention some reactor experiments here?*

COMMENT: *Should I describe the neutrino-on-electron scattering here? - I should definitely mention it as one of the detection methods. Not sure how much I should talk about it. Leave the details to the last chapter...* [12] nu-on-e is for example used for the detection of solar neutrinos in the Kamiokande experiments Nu-on-e is mainly sensitive to electron neutrinos, whose cross section is about 6 times larger than for the muon/tau neutrinos.

The first electron neutrino detection was by the Homestake neutrino experiment detecting solar neutrinos [19] $\nu_e + n \to p + e^-$

Leon Lederman, Jack Steinberger and others joined Schwartz and using a spark chamber detector in 1962 observed [20] for the first time the muon neutrino ν_μ. Atmospheric neutrinos were first observed by the Kolar Gold Field Mine in South India [21, 22] and in the East Rand Proprietary Gold Mine in South Africa [23].

In 1990 the L3 Collaboration studied properties of the Z^0 boson and fitted to its peak cross-section and decay width to determine the total number of active (interacting with Z^0) light ($m_\nu < m_Z/2$) neutrino flavours (N_ν). They found the best fit integer value to be 3 and ruled out the possibility of four or more active light neutrino flavours at 4σ [24]. Latest most precise results put the fitted value to $N_\nu = 2.9840 \pm 0.0082$ [25]. After this result it was only a matter of time, before the third neutrino, the tau neutrino (ν_τ) was discovered. Evidence for that were shown in 2000 from the DONUT Collaboration at Fermilab [26].

I think I should mention here the basic neutrino interactions and their corresponding cross section. For neutrino on nucleons, the total cross section per neutrino energy is around $0.7 \times 10^{-38}\,\mathrm{cm}^2\mathrm{GeV}^{-1}$ for neutrinos and half that for antineutrinos. For neutrino on electron interactions, the total cross section per neutrino energy is more similar to $10^-41 - 10^{-42}\,\mathrm{cm}^2\mathrm{GeV}^{-1}$.

The main neutrino interactions are

$$\nu_l + n \to p + l^- \tag{1.11}$$

$$\overline{\nu}_l + p \to n + l^+ \tag{1.12}$$

$$\nu_l + N \to \nu_l + N \tag{1.13}$$

$$\overline{\nu}_l + N \to \overline{\nu}_l + N \tag{1.14}$$

For neutrinos interacting on the nuclei, we distinguish between different types of interactions based on what happens to the nucleus. If it's an interaction with a single proton or neutron, we call this Quasi Elastic (QE) interaction. If this proton gets excited into a Δ resonance (which then generally decays into a π), we call this Resonant production, if neutrino penetrates through the nucleon and interacts directly with a quark inside it, we call this Deep Inelastic Scattering (DIS) interaction. This is shown on Fig. 1.2. There can be additional subtypes due to nuclear effects, namely the 2p2h interaction TO DO: *Find a reference for the 2p2h* also called Meson Exchange Current

(MEC), or possible Final State Interaction (FSI).

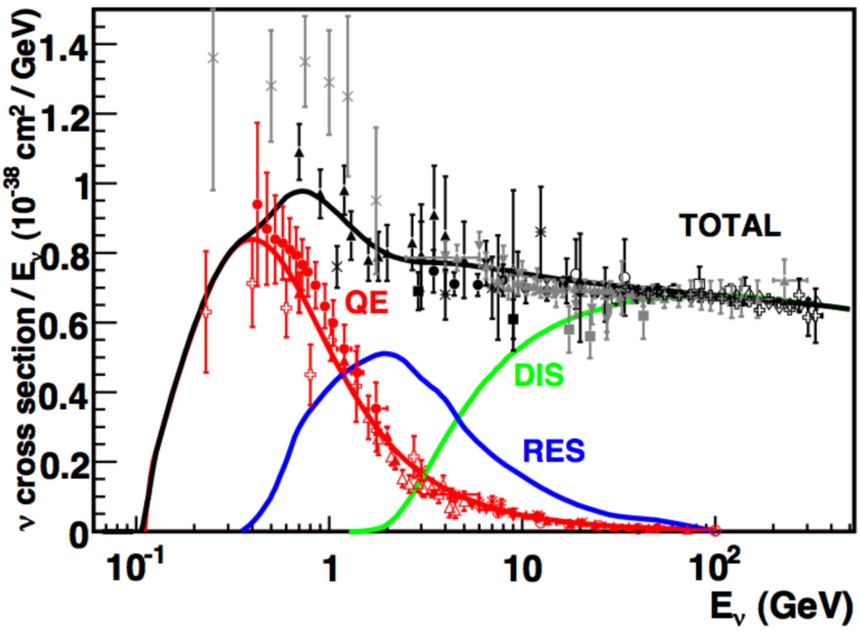

Figure 1.2: Neutrino CC cross sections based on the interaction types. Figure from [27] compares the measured data [16] and the prediction [28]

Problems of the SM

TO DO: *Describe neutrino interactions, CC, NC elastic. QE, Res., DIS. Also nuclear effects - MEC, FSI,...*

1.3 Neutrino Oscillation

Neutrino oscillate and therefore have mass. Describe neutrino oscillations and the current status of their measurements. Maybe also when they were discovered and how?

[Master's] Several experimental indications for neutrino oscillations were found shortly after its theoretical predictions. Already in 1968 their Homestake Solar Neutrino Observatory saw a solar neutrino flux less than 3 Solar Neutrino Units (SNU = one interaction per 10^{36} target atoms s^{-1}), well below the solar model prediction of the time [19]. This discrepancy became the *"solar neutrino problem"*, which is in line with neutrino oscillations, but no direct implications could have been drawn since it might have been caused by a lack of understanding of nuclear physics, astrophysics of the Sun, or particle physics of the neutrino[14]. Kamiokande experiment, which confirmed the results from Homestake [29].

The Solar neutrino anomaly was also resolved, when the Sudbury Neutrino Observatory (SNO) provided $> 5\sigma$ evidence for solar ν_e oscillations in 2002, independent on the solar model [30]. While other solar neutrino experiments measured solar ν_e only via the charged current (CC) interactions

$$\nu_e + n \rightarrow p + e^- \qquad (CC), \tag{1.15}$$

SNO had an ability to also detect neutrinos via the neutral current (NC) interaction

$$\nu + X \rightarrow \nu + X' \qquad (NC), \tag{1.16}$$

which are equally sensitive to all active neutrino flavours and their rate is therefore unaffected by standard neutrino oscillations. SNO could compare CC and NC event rates and conclude that ν_e from the Sun oscillate into other neutrino flavours along the way [30].

Measuring atmospheric neutrinos brought about another neutrino conundrum, the *Atmospheric neutrino anomaly*. It came from the disagreement between experiments such as NUSEX[31] and Fréjus[32], which used iron calorimeters detectors, and experiments IMP[33] and Kamiokande[34], which used water Cherenkov detectors. All of these experiments were looking for a deficit of ν_μ, or an excess of ν_e, compared to prediction. While the first two experiments saw a good agreement between experimental results and predictions, the latter two did not and suggested the possibility of neutrino oscillations, which could explain their disagreement. Solution to the Atmospheric neutrino anomaly came in 1998, when the Super-Kamiokande (SK) experiment showed for the first time the experimental evidence for neutrino oscillations [35]. SK has however also disfavoured the two neutrino hypothesis, with regards to the existence of an additional neutrino flavour.

The idea that neutrinos can oscillate between the individual flavours originates [36, 37] from the $K^0 \leftrightarrow \overline{K^0}$ oscillations, which was adapted to neutrinos [38, 39] by considering that the weak interaction neutrino eigenstates ν_α produced in CC weak interaction are not identical to the mass neutrino eigenstates ν_k and are related by

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle \,. \tag{1.17}$$

Here U is a unitary matrix now know by the authors of neutrino oscillations as Pontecorvo Maki Nakagawa Sakata (PMNS) matrix [12, 40].

The massive neutrino states $|\nu_i\rangle$ are eigenstates of the hamiltonian

$$\mathcal{H}\left|\nu_k\right\rangle = E_i \left|\nu_k\right\rangle , \tag{1.18}$$

where

$$E_k = \sqrt{\overrightarrow{p}^2 + m_k^2} \tag{1.19}$$

and since neutrinos are generally ultrarelativistic, we can approximate their energy as

$$E_k \xrightarrow{m^2 \ll p^2 \approx E} E + \frac{m_k^2}{E}. \tag{1.20}$$

From the Schrodinger equation

$$i\frac{d}{dt}\left|\nu_k(t)\right\rangle = \mathcal{H}\left|\nu_k(t)\right\rangle \tag{1.21}$$

we get that the massive neutrino states evolve as plane waves

$$\left|\nu_k(t)\right\rangle = e^{-iE_k t}\left|\nu_k\right\rangle . \tag{1.22}$$

Also thanks to the unitarity of the mixing matrix we get

$$\left|\nu_k\right\rangle = \sum_\alpha U_{\alpha k}\left|\nu_\alpha\right\rangle \tag{1.23}$$

and therefore

$$\left|\nu_\alpha(t)\right\rangle = \sum_\beta \sum_k U_{\alpha k}^* U_{\beta k} e^{-iE_k t}\left|\nu_\beta\right\rangle . \tag{1.24}$$

Since both the massive neutrino states and the flavour neutrino states are built in an orthogonal basis $\langle\nu_k|\nu_j\rangle = \delta_{kj}$ and $\langle\nu_\alpha|\nu_\beta\rangle = \delta_{\alpha\beta}$ we can write the amplitude of $\nu_\alpha \to \nu_\beta$ as

$$A_{\nu_\alpha\to\nu_\beta}(t) \equiv \langle\nu_\beta|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^* U_{\beta k} e^{-iE_k t} \tag{1.25}$$

Given the ultrarelativistic approximation in Eq. 1.20, assuming the time t is equivalent to the distance L, which is easier to measure in an experiment, we get the probability that ν_α oscillates into ν_beta over the course of distance L with an energy E is

Neutrino ν_α can oscillate and therefore be detected as a different neutrino flavour ν_β with a probability

$$P_{\nu_\alpha\to\nu_\beta}(L) = \left|A_{\nu_alpha\to\nu_\beta}(t)\right|^2 = \sum_{k,j} U^*_{\alpha k}U_{\beta j}U_{\alpha j}U^*_{\beta j}e^{-i(E_k-E_j)L} \tag{1.26}$$

$$= \sum_{k,j} U^*_{\alpha k}U_{\beta j}U_{\alpha j}U^*_{\beta j}e^{-i\frac{\Delta m^2_{kj}L}{2E}} \tag{1.27}$$

where we defined

$$\Delta m^2_{kj} \equiv m^2_k - m^2_j. \tag{1.28}$$

Oscillation probability can be also expressed as

$$\begin{aligned} P_{\nu_\alpha\to\nu_\beta}(L) = \delta_{\alpha\beta} &- 4\sum_{i>j}\text{Re}\left(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right)\sin^2\Delta_{ij} \\ &+ 2\sum_{i>j}\text{Im}\left(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right)\sin 2\Delta_{ij}, \end{aligned} \tag{1.29}$$

where[40]

$$\Delta_{ij} \equiv \Delta m^2_{ij}\frac{L}{4E} = 1.267\frac{\Delta m^2_{ij}}{\text{eV}^2}\frac{L/E}{\text{m/MeV}}.$$

Since real neutrino beams are not monochromatic, what is measured in experiments is an **average** oscillation probability with $\langle\sin^2\Delta_{ij}\rangle$ and $\langle\sin 2\Delta_{ij}\rangle$ in eq.1.29. We can notice that if $E/L \gg \Delta m^2_{ij}$ the oscillation does not show any effect yet and if $E/L \ll \Delta m^2_{ij}$ the oscillating phase goes through many cycles and is averaged to $\langle\sin^2\Delta_{ij}\rangle = 1/2$. Therefore different experimental settings can measure different oscillation parameters [41].

The PMNS matrix describing neutrino oscillations in the so called 3ν para-digm depends on six independent parameters: 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and 3 phases. One of the phases is δ_{CP}, which, if different from 0 or π, implies CP violation, and the other two are α and β, so called Majorana phases, which are non zero only if neutrinos are Majorana (neutrinos and antineutrinos are described by just one field, i.e. neutrinos are the same particle as antineutrinos). Majorana phases play no role in neutrino oscillations, so they are usually left out in the description [41]. The PMNS matrix in this case can be parametrized as

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}, \tag{1.30}$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$.

Other than the PMNS matrix, neutrino oscillations depend on the mass squared differences (eq.1.28). In case of 3 neutrinos, those are Δm^2_{21} and Δm^2_{31}. Δm^2_{21} mainly drives oscillations of solar neutrinos and is therefore often denoted as $\Delta m^2_{\odot}$ or Δm^2_{sol}, while Δm^2_{31} drives oscillations on the scale for atmospheric neutrinos and is often written as Δm^2_{atm} [40]. There can only be two independent mass squared differences for oscillation of three neutrinos, since

$$\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = 0. \tag{1.31}$$

1.3.1 The Matter Effect

Possible explanation of the Solar neutrino problem was proposed in 1978 by L. Wolfenstein, who considered the effect of matter on neutrino oscillations [42]. His modification of neutrino oscillations when passing through matter arises from the coherent forward scattering of electron neutrinos, as a result of their charged current (CC) interaction with electrons, which are abundant in matter, as opposed to other lepton flavours, muons and tauons, resulting in an imbalance between ν_e and ν_μ/ν_τ. This manifests as an effective potential, which depends on the density and composition of the matter [42]. This idea was later further developed for neutrinos passing through the Sun by Mikheyev and Smirnov in 1985 [43][40] and we now call this effect the Mikheyev-Smirnov-Wolfenstein (MSW) effect.

To showcase this effect we consider only two neutrino flavours, ν_e and ν_X, where X denotes a combination of all other non-electron flavours. Vacuum oscillations are in this two-neutrino approximation driven by a single mass splitting Δm^2 and the corresponding PMNS matrix is a rotational matrix parametrized by one angle θ:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}. \tag{1.32}$$

The MSW effect can be described as the presence of an Effective Potential [44]

$$V = \pm\sqrt{2}G_F N_e = \pm 3.8 \times 10^{-14} \left(\frac{\rho}{\text{g cm}^{-3}}\right)\left(\frac{Y_e}{0.5}\right) \text{eV}, \tag{1.33}$$

where G_F is the Fermi coupling constant, N_e is the electron density, Y_e is the electron number per nucleon and plus or minus sign is for neutrinos or antineutrinos respectively.

This potential can be seen as having the effect of modifying the Δm^2 and θ of the neutrino oscillations: [44]

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta \mp \xi)^2} \tag{1.34}$$

$$\left(\Delta m^2\right)_{\mathit{eff}} = \Delta m^2 \times \sqrt{\sin^2 2\Theta + (\cos 2\theta \mp \xi)^2}, \tag{1.35}$$

where

$$\xi = \frac{2\sqrt{2}G_F N_e}{\Delta m^2}. \tag{1.36}$$

Need to mention the importance of the δ_{CP} measurements, maybe even the Sakharov conditions... Also why do we care about the Δm^2 or the octants and what are those... Maybe cite the Snowmass report and the PDG.

1.4 Neutrino Mass

Experiments for their values? Theoretical predictions for how they obtained them

Theories of neutrino mass generation

[Fundamentals of neutrinos physics and astrophysics] The only extension of the SM that is needed is the introduction of right-handed components $\nu_{\alpha R}$ of the neutrino fields. Such a model is sometimes called the *minimally extended Standard Model*. The right handed neutrino fields are fundamentally different from the other elementary fermion fields because they are invariant under the symmetries of the SM: they are **singlets** of $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L$ and have hypercharge $Y = 0$. The right handed neutrino fields are called sterile [883] because they do not participate in weak interactions and their only interaction is gravitational. their right handedness is not required though! could also be left handed but have to be singlets and therefore sterile!

In the minimally extended standard model with three right handed neutrino fields, the SM Higgs-lepton Yukawa Lagrangian is extended by adding a lepton term with the same structure as the second term on the right handed side, which generates the masses of up-type quarks

$$\mathcal{L}_Y = - \sum_{\alpha,\beta=e,\mu,\tau} Y'^{l}_{\alpha\beta} \overline{L}_{\alpha L} \Phi l'_{\beta R} - \sum_{\alpha,\beta=e,\mu,\tau} Y'^{\nu}_{\alpha\beta} \overline{L}_{\alpha L} \tilde{\Phi} \nu'_{\beta R} + \text{h.c.}, \tag{1.37}$$

where Y'^{ν} is a new matrix of Yukawa couplings.

Using the unitary gauge we can diagonalize the Yukawa couplings we obtain

$$\mathcal{L}_Y = - \sum_{\alpha=e,\mu,\tau} \frac{y^l_\alpha v}{\sqrt{2}} \bar{l}_\alpha l_\alpha - \sum_{k=1}^{N} \frac{y^\nu_k v}{\sqrt{2}} \overline{\nu}_k \nu_k - \sum_{\alpha=e,\mu,\tau} \frac{y^l_\alpha}{\sqrt{2}} \bar{l}_\alpha l_\alpha H - \sum_{k=1}^{N} \frac{y^\nu_k}{\sqrt{2}} \overline{\nu}_k \nu_k H \tag{1.38}$$

Therefore the neutrino masses are given by

$$m_k = \frac{y^\nu_k v}{\sqrt{2}} \quad (k = 1, ..., N)\,, \tag{1.39}$$

and massive Dirac neutrinos couple to the Higgs field through the last term. Note that the neutrinos masses are proportional to the Higgs VEV v, as the masses of charged leptons and quarks. However, it is known that the masses of neutrinos are much smaller than those of charged leptons and quarks, but there is no explanations here of the very small values of the eigenvalues Y^ν_k of the Higgs-neutrino Yukawa coupling matrix that are needed. The lagrangian defined this way does not conserve the lepton flavour number, which leads to neutrino oscillations. The Dirac character of massive neutrinos is closely related to the invariance of the total Lagrangian under the global U(1) gauge transformations.

The sterile neutrino fields do not participate in weak interaction with both their left and right components, but can couple with the ordinary neutrinos through the mass therm, generating a complicated mixing between active and sterile degrees of freedom.Since at present there is no indication of the existence of such additional sterile Dirac neutrino fields, ockham's razor suggests to ignore them...

1.4.1 Majorana neutrinos

[Fundamentals of neutrinos physics and astrophysics,p.190] If the neutrino is massless, since the left handed chiral component of the neutrino field obeys the Weyl equation in both the Dirac and Majorana descriptions and the right handed chiral component is irrelevant for neutrino interactions, the Dirac and Majorana theories are physically equivalent. From this it is clear that in practice one can distinguish a Dirac from a Majorana neutrino only by measuring some effect due to the neutrino mass. Moreover, the mass effect must not be of kinematical nature, because the kinematical effects of Dirac and Majorana masses are the same. For example, the Dirac and Majorana nature of neutrinos cannot be revealed through neutrino oscillations! The most promising way to find if neutrinos are Majorana particles is the search for neutrinoless double beta decay.

[OverviewOfNeutrinoPhysicsPheno2024.pdf] In contrast, the Majorana phases do not enter the flavour neutrino oscillation probabilities [22, 85], but contribute to the $\beta\beta_{0\nu}$ decay rate

Acronyms

CC Charged current. 2, 6, 7

DIS Deep Inelastic Scattering. 5

FSI Final State Interaction. 6

MEC Meson Exchange Current. 5

NC Neutral Current. 2

PMNS Pontecorvo Maki Nakagawa Sakata. 8

QE Quasi Elastic (interaction). 5

SM Standard Model. 2, 3

Bibliography

[1] Wolfgang Pauli. Pauli letter collection: letter to Lise Meitner. Typed copy. URL http://cds.cern.ch/record/83282.

[2] L. M. Brown. The idea of the neutrino. *Physics Today*, 31(9):23–28, September 1978. doi:10.1063/1.2995181. (Including translation of W. Pauli, Aufsdtze und Vortrdge u'ber Physik und Erkenntnistheorie, Braunschweig (1961)).

[3] H. A. Bethe. Ionization power of a neutrino with magnetic moment. *Mathematical Proceedings of the Cambridge Philosophical Society*, 31(1):108–115, 1935. doi:10.1017/S0305004100012998.

[4] Enrico Fermi. Tentativo di una teoria dei raggi β. 11(1):1–19. ISSN 1827-6121. doi:10.1007/BF02959820.

[5] Fred L. Wilson. Fermi's theory of beta decay. *American Journal of Physics*, 36 (12):1150–1160, 1968. doi:10.1119/1.1974382. (A complete English translation of E.Fermi, Zeitschrift fur Physik 88, 161 (1934)).

[6] L. Landau. On the conservation laws for weak interactions. 3(1):127–131. ISSN 0029-5582. doi:https://doi.org/10.1016/0029-5582(57)90061-5. URL https://www.sciencedirect.com/science/article/pii/0029558257900615.

[7] T. D. Lee and C. N. Yang. Parity nonconservation and a two-component theory of the neutrino. *Phys. Rev.*, 105:1671–1675, Mar 1957. doi:10.1103/PhysRev.105.1671. URL https://link.aps.org/doi/10.1103/PhysRev.105.1671.

[8] Abdus Salam. On parity conservation and neutrino mass. *Nuovo Cim.*, 5:299–301, 1957. doi:10.1007/BF02812841.

[9] Sheldon L. Glashow. Partial-symmetries of weak interactions. 22(4):579–588. ISSN 0029-5582. doi:https://doi.org/10.1016/0029-5582(61)90469-2. URL https://www.sciencedirect.com/science/article/pii/0029558261904692.

[10] Steven Weinberg. A model of leptons. *Phys. Rev. Lett.*, 19:1264–1266, Nov 1967. doi:10.1103/PhysRevLett.19.1264. URL https://link.aps.org/doi/10.1103/PhysRevLett.19.1264.

[11] Abdus Salam. *Weak and electromagnetic interactions*, pages 244–254. doi:10.1142/9789812795915_0034. URL https://www.worldscientific.com/doi/abs/10.1142/9789812795915_0034.

[12] Carlo Giunti and Chung W. Kim. *Fundamentals of Neutrino Physics and Astrophysics*. 2007. ISBN 978-0-19-850871-7.

[13] F. Reines and C.L. Cowan. Neutrino physics. *Physics Today*, 10(8):12–18, 1957. doi:10.1063/1.3060455.

[14] M. C. Goodman. Resource letter anp-1: Advances in neutrino physics. *American Journal of Physics*, 84:309–319, 2016. doi:10.1119/1.4962228.

[15] M. Schwartz. Feasibility of using high-energy neutrinos to study the weak interactions. *Phys. Rev. Lett.*, 4:306–307, Mar 1960. doi:10.1103/PhysRevLett.4.306. URL https://link.aps.org/doi/10.1103/PhysRevLett.4.306.

[16] J. A. Formaggio and G. P. Zeller. From ev to eev: Neutrino cross sections across energy scales. *Rev. Mod. Phys.*, 84:1307–1341, Sep 2012. doi:10.1103/RevModPhys.84.1307. URL https://link.aps.org/doi/10.1103/RevModPhys.84.1307.

[17] F. Reines and C. L. Cowan. Detection of the free neutrino. *Phys. Rev.*, 92:830–831, Nov 1953. doi:10.1103/PhysRev.92.830. URL https://link.aps.org/doi/10.1103/PhysRev.92.830.

[18] Cowan Jr. C.L., Reines F., Harrison F.B., Kruse H.W., and McGuire A.D. Detection of the free neutrino: A confirmation. *Science*, 124(3212):103–104, July 1956. doi:10.1126/science.124.3212.103.

[19] Jr. Davis, Raymond, Don S. Harmer, and Kenneth C. Hoffman. Search for neutrinos from the sun. *Phys. Rev. Lett.*, 20:1205–1209, 1968. doi:10.1103/PhysRevLett.20.1205.

[20] G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz, and J. Steinberger. Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos. *Phys. Rev. Lett.*, 9:36–44, Jul 1962. doi:10.1103/PhysRevLett.9.36. URL https://link.aps.org/doi/10.1103/PhysRevLett.9.36.

[21] C.V. Achar, M.G.K. Menon, V.S. Narasimham, P.V.Ramana Murthy, B.V. Sreekantan, K. Hinotani, S. Miyake, D.R. Creed, J.L. Osborne, J.B.M. Pattison, and A.W. Wolfendale. Detection of muons produced by cosmic ray neutrinos deep underground. 18(2):196–199. ISSN 0031-9163. doi:https://doi.org/10.1016/0031-9163(65)90712-2. URL https://www.sciencedirect.com/science/article/pii/0031916365907122.

[22] C. V. Achar et al. Observation of a non-elastic cosmic ray neutrino interaction. *Phys. Lett.*, 19:78–80, 1965. doi:10.1016/0031-9163(65)90969-8.

[23] F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, G. R. Smith, J. P. F. Sellschop, and B. Meyer. Evidence for high-energy cosmic-ray neutrino interactions. *Phys. Rev. Lett.*, 15:429–433, Aug 1965. doi:10.1103/PhysRevLett.15.429. URL https://link.aps.org/doi/10.1103/PhysRevLett.15.429.

[24] B. Adeva et al. Measurement of Z^0 decays to hadrons and a precise determination of the number of neutrino species. *Phys. Lett. B*, 237:136–146, 1990. doi:10.1016/0370-2693(90)90476-M.

[25] S. Schael et al. Precision electroweak measurements on the Z resonance. *Phys. Rept.*, 427:257–454, 2006. doi:10.1016/j.physrep.2005.12.006.

[26] K. Kodama et al. Observation of tau neutrino interactions. *Phys. Lett. B*, 504:218–224, 2001. doi:10.1016/S0370-2693(01)00307-0.

[27] *Fundamental Physics at the Intensity Frontier*, 5 2012. doi:10.2172/1042577.

[28] D. Casper. The Nuance neutrino physics simulation, and the future. *Nucl. Phys. B Proc. Suppl.*, 112:161–170, 2002. doi:10.1016/S0920-5632(02)01756-5.

[29] Y. Fukuda et al. Solar neutrino data covering solar cycle 22. *Phys. Rev. Lett.*, 77:1683–1686, Aug 1996. doi:10.1103/PhysRevLett.77.1683. URL https://link.aps.org/doi/10.1103/PhysRevLett.77.1683.

[30] Q.R. Ahmad et al. Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.*, 89:011301, 2002. doi:10.1103/PhysRevLett.89.011301.

[31] M. Aglietta et al. Experimental study of atmospheric neutrino flux in the NUSEX experiment. *Europhysics Letters (EPL)*, 8(7):611–614, apr 1989. doi:10.1209/0295-5075/8/7/005. URL https://doi.org/10.1209%2F0295-5075%2F8%2F7%2F005.

[32] K. Daum et al. Determination of the atmospheric neutrino spectra with the fréjus detector. *Zeitschrift für Physik C Particles and Fields*, 66(3):417–428, 1995. ISSN 1431-5858. URL https://doi.org/10.1007/BF01556368.

[33] R. Becker-Szendy et al. Electron- and muon-neutrino content of the atmospheric flux. *Phys. Rev. D*, 46:3720–3724, Nov 1992. doi:10.1103/PhysRevD.46.3720. URL https://link.aps.org/doi/10.1103/PhysRevD.46.3720.

[34] Y. Fukuda et al. Atmospheric ν_μ/ν_e ratio in the multi-GeV energy range. *Phys. Lett. B*, 335(GIFU-PH-94-01. ICRR-321. INS-Rep-1035. KEK-Preprint-94-50. KOBE-AP-94-01. NGTHEP-94-1. OULNS-94-01. TIT-HPE-94-04. TKU-PAP-94-2. UPR-0226-E):237–245. 25 p, Jun 1994. URL https://cds.cern.ch/record/266736.

[35] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.*, 81:1562–1567, 1998. doi:10.1103/PhysRevLett.81.1562.

[36] B Pontecorvo. Mesonium and antimesonium. *Sov. Phys. JETP*, 33:549–551, 8 1957.

[37] B. Pontecorvo. Inverse beta processes and nonconservation of lepton charge. *Sov. Phys. JETP*, 7:172–173, 1958.

[38] Ziro Maki, Masami Nakagawa, and Shoichi Sakata. Remarks on the unified model of elementary particles. *Prog. Theor. Phys.*, 28:870–880, 1962. doi:10.1143/PTP.28.870.

[39] V. Gribov and B. Pontecorvo. Neutrino astronomy and lepton charge. 28(7):493–496. ISSN 0370-2693. doi:https://doi.org/10.1016/0370-2693(69)90525-5. URL https://www.sciencedirect.com/science/article/pii/0370269369905255.

[40] M.C. Gonzalez-Garcia and Yosef Nir. Neutrino Masses and Mixing: Evidence and Implications. *Rev. Mod. Phys.*, 75:345–402, 2003. doi:10.1103/RevModPhys.75.345.

[41] M. Tanabashi et al. Review of Particle Physics. *Phys. Rev. D*, 98(3):030001, 2018. doi:10.1103/PhysRevD.98.030001. 2019 update.

[42] L. Wolfenstein. Neutrino oscillations in matter. *Phys. Rev. D*, 17:2369–2374, May 1978. doi:10.1103/PhysRevD.17.2369. URL https://link.aps.org/doi/10.1103/PhysRevD.17.2369.

[43] S.P. Mikheyev and A.Yu. Smirnov. Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos. *Sov. J. Nucl. Phys.*, 42:913–917, 1985.

[44] *1st CERN - CLAF School of High-energy Physics*, Geneva, 2003. CERN, CERN. doi:10.5170/CERN-2003-003. URL http://cds.cern.ch/record/485010.