

I. NEUTRINO MASSES AND OSCILLATIONS

As we saw in Eq. ?? , the neutrino fields ν_α only couple to the associated lepton fields ℓ_α , conserving the lepton number L_α . We will now introduce two separate extensions to this part of the Standard Model.

We introduce a right-handed neutrino field, ν_R . It has the usual properties of the conventional left-handed neutrino such as hypercharge and color zero. Moreover, since the electroweak gauge group $SU(2)_L$ only couple to left-handed particles and right-handed antiparticles, it transforms as a singlet under the SM symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$. This neutrino is *sterile* since it doesn't participate any of the SM interactions.

We extend the SM by adding a right-handed component to the Higgs-lepton Yukawa Lagrangian from Eq. ?? with neutrino Yukawa couplings $Y_{\alpha\beta}'$,

$$\mathcal{L}_H = - \left(\frac{v+H}{\sqrt{2}} \right) [\ell'_{\alpha L} Y_{\alpha\beta}' \ell'_{\beta R} + \nu'_{\alpha L} Y_{\alpha\beta}' \nu'_{\beta R}] \quad (1)$$

Similar to how we diagonalized the lepton Yukawa couplings $Y_{\alpha\beta}'$ in Eq. ??, we diagonalize $Y_{\alpha\beta}'$ as

$$V_{\alpha k L}^{\nu\dagger} Y_{\alpha\beta}' V_{\beta j R}^\nu = Y_{kj}^\nu. \quad (2)$$

Now we introduce a crucial difference between the properties of the charged lepton and the neutrino fields. While the charged lepton flavor eigenstate was uniquely determined by its mass eigenstate, the neutrino flavor is a superposition of mass eigenstates. This is because neutrinos are indirectly detected via the observation of its associated charged lepton, so there is no requirement of neutrino flavor eigenstates to have a definite mass. The flavor of a neutrino is then, by definition, the flavor of the associated charged lepton. This is commonly introduced as giving the mass eigenstates Latin numerals and letters, while the flavor eigenstates stay as Greek letters.

So, let the neutrino field with chirality X be denoted ν_X , with components having Latin numerals to distinguish them from the flavour components, i.e

$$\nu_{kX} = V_{k\beta X}^{\nu\dagger} \nu'_{\beta X}. \quad (3)$$

The diagonalized Lagrangian now takes the form

$$\begin{aligned} \mathcal{L}_H &= - \left(\frac{v+H}{\sqrt{2}} \right) [\ell'_{\alpha L} Y_{\alpha\beta}' \ell'_{\beta R} + \nu'_{\alpha L} Y_{\alpha\beta}' \nu'_{\beta R}] \\ &= - \left(\frac{v+H}{\sqrt{2}} \right) \left[\ell'_{\alpha L} V_{\alpha\beta L}^\ell Y_{\alpha\beta}^\ell V_{\alpha\beta R}^{\ell\dagger} \ell'_{\beta R} \right. \\ &\quad \left. + \nu'_{\alpha L} V_{\alpha k L}^\nu Y_{kj}^\nu V_{\beta j R}^{\nu\dagger} \nu'_{\beta R} \right] \\ &= - \left(\frac{v+H}{\sqrt{2}} \right) [\ell_{\alpha L}^\dagger Y_{\alpha\beta}^\ell \ell_{\beta R} + \nu_{k L}^\dagger Y_{kj}^\nu \nu_{j R}] \\ &= - \left(\frac{v+H}{\sqrt{2}} \right) [\bar{\ell}_{\alpha L} Y_{\alpha\beta}^\ell \ell_{\beta R} + \bar{\nu}_{k L} Y_{kj}^\nu \nu_{j R}] \end{aligned} \quad (4)$$

By construction, $Y_{\alpha\beta}^\ell$ and Y_{kj}^ν are diagonal, so we write them as $y_\alpha^\ell \delta_{\alpha\beta}$ and $y_k^\nu \delta_{kj}$ respectively, leaving the Lagrangian as

$$\begin{aligned} \mathcal{L}_H &= - \left(\frac{v+H}{\sqrt{2}} \right) [\bar{\ell}_{\alpha L} y_\alpha^\ell \delta_{\alpha\beta} \ell_{\beta R} + \bar{\nu}_{k L} y_k^\nu \delta_{kj} \nu_{j R}] \\ &= - \left(\frac{v+H}{\sqrt{2}} \right) [\bar{\ell}_{\alpha L} y_\alpha^\ell \ell_{\alpha R} + \bar{\nu}_{k L} y_k^\nu \nu_{k R}] \\ &= - \left(\frac{v+H}{\sqrt{2}} \right) [y_\alpha^\ell \bar{\ell}_{\alpha L} \ell_{\alpha R} + y_k^\nu \bar{\nu}_{k L} \nu_{k R}] \end{aligned} \quad (5)$$

Now, the Dirac neutrino field is

$$\nu_k = \nu_{kL} + \nu_{kR}. \quad (6)$$

Multiplying ν_k with its conjugate $\bar{\nu}_k$, we get

$$\begin{aligned}\bar{\nu}_k \nu_k &= \bar{\nu}_{kL} \nu_{kL} + \bar{\nu}_{kR} \nu_{kL} + \bar{\nu}_{kL} \nu_{kR} + \bar{\nu}_{kR} \nu_{kR} \\ &= \bar{\nu}_{kL} \nu_{kR} + \bar{\nu}_{kR} \nu_{kL} \\ &= \bar{\nu}_{kL} \nu_{kR} + \text{h.c.}\end{aligned}\tag{7}$$

The same calculation for the charged lepton field yields the same result for ℓ_k . Substituting this result and expanding the Higgs VEV into the fields gives us

$$\begin{aligned}\mathcal{L}_H &= - \left(\frac{v+H}{\sqrt{2}} \right) [y_\alpha^\ell \bar{\ell}_\alpha \ell_\alpha + y_k^\nu \bar{\nu}_k \nu_k] \\ &= - \frac{y_\alpha^\ell v}{\sqrt{2}} \bar{\ell}_\alpha \ell_\alpha - \frac{y_k^\nu v}{\sqrt{2}} \bar{\nu}_k \nu_k - \frac{y_\alpha^\ell}{\sqrt{2}} \bar{\ell}_\alpha \ell_\alpha H - \frac{y_k^\nu}{\sqrt{2}} \bar{\nu}_k \nu_k H.\end{aligned}\tag{8}$$

Thus, this extension to the SM generates neutrino masses by the Higgs mechanism, in the same fashion as with the charged leptons and the quarks:

$$m_k = \frac{y_k^\nu v}{\sqrt{2}}\tag{9}$$

Substituting the new transformation from Eq. 3 into the weak charged current, we get

$$\begin{aligned}j_L^\rho &= 2\bar{\nu}'_{\alpha L} \gamma^\rho \ell'_{\alpha L} \\ &= 2\bar{\nu}_{kL} V_{k\alpha}^{\nu\prime\dagger} V_{\alpha\alpha}^{\ell\prime} \gamma^\rho \ell_{\alpha L}\end{aligned}\tag{10}$$

Call $V_{k\alpha}^{\nu\prime\dagger} V_{\alpha\alpha}^{\ell\prime} = U_{k\alpha}^\dagger$. Now, the current in Eq. 10 conserves lepton number, since the neutrino field with flavor α only couples to the lepton field with flavor α . However, the Higgs-lepton Yukawa Lagrangian in Eq. 5 violates lepton number conservation since it couples the charged lepton flavor α to the neutrino mass eigenstate k , which is a superposition of flavors. There is no transformation that leaves both the interaction and kinetic Lagrangian invariant. We now have

$$j_L^\rho = 2 \sum_\alpha \sum_k U_{\alpha k}^* \bar{\nu}_{kL} \gamma^\rho \ell_{\alpha L}\tag{11}$$

Now, the Fourier expansion of the field operator $\bar{\nu}_{kL}$ in Eq. 11 contains creation operators $a_{\nu_k}^\dagger$ of massive neutrinos with mass m_k . This means that the summation over the mass index k constructs a flavor neutrino, which interacts with the charged lepton field $\ell_{\alpha L}$. In other words, the charged current generates a flavor neutrino ν_α , which is a superposition of the mass eigenstates ν_k with weights $U_{\alpha k}^*$. In the ket-formalism, we express this as

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* |\nu_k\rangle.\tag{12}$$

It is the mass eigenstates $|\nu_k\rangle$ that are eigenstates of the Hamiltonian, with eigenvalues

$$E_k = \sqrt{\vec{p}^2 + m_k^2}.\tag{13}$$

The solution to the time-dependent Schrödinger equation

$$i \frac{d}{dt} |\nu_k(t)\rangle = H |\nu_k(t)\rangle,\tag{14}$$

gives us a plane wave evolution to the mass states as

$$|\nu_k(t)\rangle = e^{-iE_k t} |\nu_k\rangle.\tag{15}$$

Inserting the plane wave solution into Eq. 12, we get

$$|\nu_\alpha(t)\rangle = \sum_k U_{\alpha k}^* e^{-iE_k t} |\nu_k\rangle.\tag{16}$$

Now we know how to evolve and combine the mass eigenstates to form a flavor eigenstate, but how about the reverse? We swap the index $k \rightarrow j$ in Eq. 12 and multiply by $U_{\alpha k}$:

$$\begin{aligned}\sum_{\alpha} U_{\alpha k} |\nu_{\alpha}\rangle &= \sum_{\alpha, j} U_{\alpha k} U_{\alpha j}^* |\nu_j\rangle \\ \sum_{\alpha} U_{\alpha k} |\nu_{\alpha}\rangle &= \sum_j \delta_{kj} |\nu_j\rangle \\ \sum_{\alpha} U_{\alpha k} |\nu_{\alpha}\rangle &= |\nu_k\rangle ,\end{aligned}\tag{17}$$

where we have used the unitarity of the leptonic mixing matrix. Eqs. 12 and 16 yield

$$\begin{aligned}|\nu_{\alpha}(t)\rangle &= \sum_k U_{\alpha k}^* e^{-iE_k t} |\nu_k\rangle \\ |\nu_{\alpha}(t)\rangle &= \sum_k U_{\alpha k}^* e^{-iE_k t} \left(\sum_{\beta} U_{\beta k} |\nu_{\beta}\rangle \right) \\ |\nu_{\alpha}(t)\rangle &= \sum_{k, \beta} U_{\alpha k}^* U_{\beta k} e^{-iE_k t} |\nu_{\beta}\rangle .\end{aligned}\tag{18}$$

The probability of the flavor transition $\nu_{\alpha} \rightarrow \nu_{\beta}$ at time t is $|\langle \nu_{\beta} | \nu_{\alpha}(t) \rangle|^2$:

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(t) = \sum_{k, j} U_{\alpha k}^* U_{\beta k} U_{\beta j}^* U_{\alpha j} e^{-i(E_k - E_j)t} .\tag{19}$$

We assume the neutrino masses m_k to be extremely small compared to their associated energies E_k . Thus, $v \approx 1$, and $|\vec{p}| \approx E$ making the energy-dispersion relation of Eq. 13 to first order:

$$\begin{aligned}E_k &= \sqrt{\vec{p}^2 + m_k^2} \\ &= \vec{p}^2 \sqrt{1 + \frac{m_k^2}{\vec{p}^2}} \\ &\approx E + \frac{m_k^2}{2E}\end{aligned}\tag{20}$$

Hence, the exponential can be simplified, and simplifying the notation $P_{\nu_{\alpha} \rightarrow \nu_{\beta}}(t) \rightarrow P_{\alpha\beta}(t)$ we get

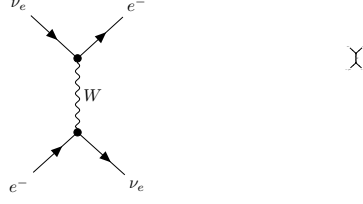
$$P_{\alpha\beta}(t) = \sum_{k, j} U_{\alpha k}^* U_{\beta k} U_{\beta j}^* U_{\alpha j} e^{-i(m_k^2 - m_j^2)t/2E} .\tag{21}$$

Now, our approximation $v \approx 1$ implies $x \approx t$, thus

$$\begin{aligned}P_{\alpha\beta}(x) &= \sum_{k, j} U_{\alpha k}^* U_{\beta k} U_{\beta j}^* U_{\alpha j} e^{-i(m_k^2 - m_j^2)x/2E} \\ &= \sum_{k, j} U_{\alpha k}^* U_{\beta k} U_{\beta j}^* U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 x}{2E}\right),\end{aligned}\tag{22}$$

where we in the last step have defined the *mass squared-difference* $\Delta m_{kj}^2 = m_k^2 - m_j^2$. Thus, it is impossible to measure the mass states m_k through neutrino oscillations, since they depend on the difference between the two squared mass states instead of the masses themselves. Squaring the unitarity condition $\sum_k U_{\alpha k} U_{\beta k}^* = \delta_{\alpha\beta}$ yields

$$\sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 = \delta_{\alpha\beta} - 2 \sum_{k > j} \text{Re}[U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*]\tag{23}$$



In this work, we will always assume the mixing matrix U to be real. We thus write

$$\begin{aligned}
P_{\alpha\beta} &= \sum_{k,j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 x}{2E}\right) \\
&= \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2 + \\
&\quad + \sum_{k \neq j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 x}{2E}\right) \\
&= \delta_{\alpha\beta} - 2 \sum_{k>j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \\
&\quad + \sum_{k \neq j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 x}{2E}\right) \\
&= \delta_{\alpha\beta} - 2 \sum_{k>j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \\
&\quad + 2 \sum_{k>j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \exp\left(-i \frac{\Delta m_{kj}^2 x}{2E}\right) \\
&= \delta_{\alpha\beta} - 2 \sum_{k>j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \left[1 - \exp\left(-i \frac{\Delta m_{kj}^2 x}{2E}\right)\right] \\
&= \delta_{\alpha\beta} - 2 \sum_{k>j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \left[1 - \cos\left(\frac{\Delta m_{kj}^2 x}{2E}\right)\right] \\
&= \delta_{\alpha\beta} - 2 \sum_{k>j} U_{\alpha k} U_{\beta k} U_{\beta j} U_{\alpha j} \sin^2\left(\frac{\Delta m_{kj}^2 x}{4E}\right), \tag{24}
\end{aligned}$$

which is the probability of neutrino vacuum oscillations. The calculation for antineutrinos yield the same result if one assumes the realness of the mixing matrix.

A. Matter effects

In this work, we are concerned about the interactions with the neutrino and Earth-like matter, i.e. electrons, protons, and neutrons. The possible interactions are shown in Fig. 1A. The left panel shows that the only flavor that can go through charged current (CC) interactions is the electron flavor. This is because the Earth doesn't consist of any muons or tau particles. The right panel shows any neutrino flavor interaction via the neutral current (NC) with Earth-like matter, mediated by the neutral Z boson we see weak forward CC and NC scattering. The interaction mediated by the W boson will give rise to an effective matter potential V_{CC} , while the Z boson is responsible for V_{NC} . Our task is now to find expressions for these.

B. Effective matter potentials

We start with the effective Hamiltonian for the CC process. The Feynman rules for the left panel give us

$$H = \frac{G_F}{\sqrt{2}} [\bar{\nu}_e \gamma^\rho (1 - \gamma^5) e] [\bar{e} \gamma_\rho (1 - \gamma^5) \nu_e] \quad (25)$$

By using the Fierz transformation

$$\mathcal{L}^{V-A}(\psi_1, \psi_2, \psi_3, \psi_4) = \mathcal{L}^{V-A}(\psi_1, \psi_4, \psi_3, \psi_2), \quad (26)$$

we can permute the terms inside the brackets, yielding

$$H = \frac{G_F}{\sqrt{2}} [\bar{\nu}_e \gamma^\rho (1 - \gamma^5) \nu_e] [\bar{e} \gamma_\rho (1 - \gamma^5) e]. \quad (27)$$

Now, let's consider a finite volume V with electron states defined as

$$|e(p_e, h_e)\rangle = \frac{1}{2E_e V} a_e^{(h_e)\dagger}(p_e) |0\rangle, \quad (28)$$

i.e. using the creation operator $a_e^{(h_e)\dagger}(p_e)$ to create electron states from vacuum with momenta p_e , energy E_e , and helicity h_e . The density distribution of electrons in V is $f(E_e, T)$, which we normalize to the total number of electrons as we integrate out the momenta p_e :

$$\int d^3p_e f(E_e, T) = N_e V = n_e \quad (29)$$

Here, the electron density N_e will ultimately determine the strength of the effective matter potential. To obtain the average effective Hamiltonian, project it on the electron states in Eq. 28 and integrate over the density and sum over the helicities:

$$\begin{aligned} \bar{H} &= \int d^3p_e \langle e(p_e, h_e) | \times \frac{1}{2} \sum_{h_e} H f(E_e, T) | e(p_e, h_e) \rangle \\ &= \frac{G_F}{\sqrt{2}} \int d^3p_e \langle e(p_e, h_e) | [\bar{\nu}_e \gamma^\rho (1 - \gamma^5) \nu_e] f(E_e, T) \times \frac{1}{2} \sum_{h_e} [\bar{e}(x) \gamma_\rho (1 - \gamma^5) e(x)] | e(p_e, h_e) \rangle \\ &= \frac{G_F}{\sqrt{2}} \bar{\nu}_e \gamma^\rho (1 - \gamma^5) \nu_e \int d^3p_e f(E_e, T) \times \frac{1}{2} \sum_{h_e} \langle e(p_e, h_e) | \bar{e}(x) \gamma_\rho (1 - \gamma^5) e(x) | e(p_e, h_e) \rangle. \end{aligned} \quad (30)$$

First, calculate the sum using trace technology

$$\begin{aligned} \frac{1}{2} \sum_{h_e} \langle e(p_e, h_e) | \bar{e}(x) \gamma_\rho (1 - \gamma^5) e(x) | e(p_e, h_e) \rangle &= \frac{1}{4E_e V} \sum_{h_e} \bar{u}_e^{h_e}(p_e) \gamma_\rho (1 - \gamma^5) u_e^{h_e}(p_e) \\ &= \frac{1}{4E_e V} \text{Tr} \left[\sum_{h_e} \bar{u}_e^{h_e}(p_e) u_e^{h_e}(p_e) \gamma_\rho (1 - \gamma^5) \right] \\ &= \frac{1}{4E_e V} \text{Tr} [(\not{p}_e + m_e) \gamma_\rho (1 - \gamma^5)] \\ &= \frac{(p_e)_\rho}{E_e V} \end{aligned} \quad (31)$$

Eq. 30 now becomes

$$\langle H \rangle = \frac{G_F}{\sqrt{2} E_e V} \bar{\nu}_e (1 - \gamma^5) \nu_e \int d^3p_e \not{p}_e f(E_e, T). \quad (32)$$

Expand the integral, and use the fact that \vec{p}_e is odd:

$$\begin{aligned}
\int d^3p_e \not{p}_e f(E_e, T) &= \int d^3p_e f(E_e, T) (\gamma^0 E_e - \vec{p}_e \cdot \vec{\gamma}) \\
&= \int d^3p_e f(E_e, T) \gamma^0 E_e \\
&= \gamma_0 E_e N_e V.
\end{aligned} \tag{33}$$

Inserting this into Eq. 32, we have

$$\begin{aligned}
\langle H \rangle &= \frac{G_F N_e}{\sqrt{2}} \bar{\nu}_e (1 - \gamma^5) \nu_e \gamma_0 \\
&= \sqrt{2} G_F N_e \bar{\nu}_{Le} \gamma^0 \nu_{Le},
\end{aligned} \tag{34}$$

where the projection operator $(1 - \gamma^5)$ ensures that only the left-hand component of the neutrino fields interact weakly. Thus

$$V_{CC} = \sqrt{2} G_F N_e \tag{35}$$

For neutral current, we replace the electron field $e(x)$ in Eq. 27 by the fermion field $f(x)$, and the projection operator $(1 - \gamma^5)$ with $(g_V^f - g_A^f \gamma^5)$. Again, the γ^5 will cause the spacial component of p_f to disappear after integration, and the only difference between the average effective Hamiltonian for the neutral current is then the factor g_V^f :

$$V_{NC}^f = \sqrt{2} G_F N_A g_V^f. \tag{36}$$

Summing over the fermions, and assuming electrical neutrality and equal abundance of protons and neutrons, we have

$$\begin{aligned}
V_{NC} &= \sum_{f \in e, p, n} V_{NC}^f \\
&= \sqrt{2} G_F N_A \sum_{f \in e, p, n} g_V^f \\
&= \sqrt{2} G_F N_A \left[-\frac{1}{2} + 2 \sin^2(\theta_W) + \frac{1}{2} - 2 \sin^2(\theta_W) - \frac{1}{2} \right] \\
&= -\frac{1}{\sqrt{2}} G_F N_e,
\end{aligned} \tag{37}$$

where the electrical neutrality condition allows us to simply sum the vectorial couplings together, cancelling the electron and proton contributions (and hence, also the mixing angle dependence).

C. Matter oscillations

Since only ν_e undergo CC interactions, the V_{CC} potential is zero for all other flavors. However, since all flavors, undergo NC interactions the total matter potential in matrix form is:

$$V = \begin{bmatrix} V_{CC} + V_{NC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{bmatrix} \tag{38}$$