Majorana Phase and Matter Effects in Neutrino Chiral Oscillation

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1. Neutrino Chiral Oscillation

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1. Neutrino Chiral Oscillation

Equation of motion for a neutrino in free space

$$(i\partial\!\!\!/ - m)\psi = 0\,, \quad i\partial\!\!\!/\psi_L - m\psi_R = 0\,, \quad i\partial\!\!\!/\psi_R - m\psi_L = 0\,, \qquad \psi(t,\mathbf{x}) = U(t)\psi(0)e^{i\mathbf{p}\cdot\mathbf{x}}$$

$$\psi_L = \frac{1-\gamma_5}{2}\psi\,, \quad \psi_R = \frac{1+\gamma_5}{2}\psi\,, \quad \psi = \psi_L + \psi_R\,. \qquad U = e^{-iHt}\,, \quad H = \gamma^0\boldsymbol{\gamma}\cdot\mathbf{p} + m\gamma^0 = \boldsymbol{\alpha}\cdot\mathbf{p} + m\beta$$

How left-handed and right-handed are entangeled in free space?

In chiral representation:

$$\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \; \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix}, \; \gamma^5 = \begin{pmatrix} -I & 0 \\ 0 & I \end{pmatrix}$$

$$\psi^h(t,\mathbf{x}) = U(t)\psi^h(0)e^{i\mathbf{p}\cdot\mathbf{x}} = \psi^h(0)e^{-i(Et-\mathbf{p}\cdot\mathbf{x})}\,, \quad \psi^h(0) = \frac{1}{\sqrt{2E}}\begin{pmatrix} \sqrt{E - h\cdot p}\; u^h \\ \sqrt{E + h\cdot p}\; u^h \end{pmatrix}$$

$\psi(0)^\dagger\psi(0) = 1.$ $h = \pm 1$ - helicity, $\mathbf{p}\cdot\boldsymbol{\sigma}u^h = (h\cdot p)u^h$, $\mathbf{p} = (p_x, p_y, p_z) = p(\cos\phi\sin\theta, \sin\phi\sin\theta, \cos\theta)$.

$$u^{h=+1} = \begin{pmatrix} \cos(\theta/2) \\ \sin(\theta/2)e^{i\phi} \end{pmatrix}, \quad u^{h=-1} = \begin{pmatrix} -\sin(\theta/2)e^{-i\phi} \\ \cos(\theta/2) \end{pmatrix},$$

Oscilation probability from i to k for Dirac neutrinos:

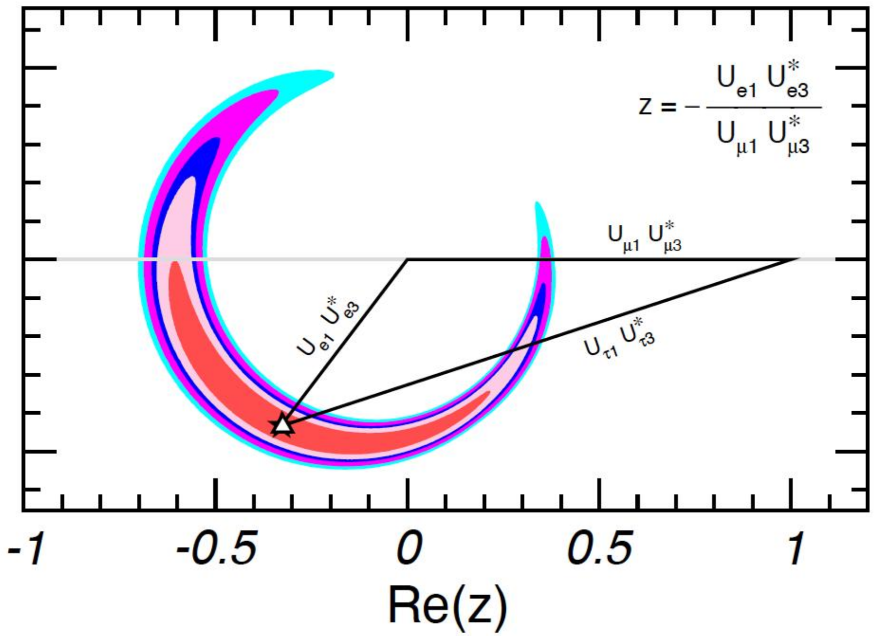
$$P(\psi_i \to \psi_k) = |<\psi(0)_k|\psi(t)_i>|^2 = |\sum V_{ij}V_{kj}^* e^{-i(E_j t - \mathbf{p}\cdot\mathbf{x})}|^2$$

Neutrion oscillations with 3 generations

$$\begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{\rm CP}} \\ -s_{12}\, c_{23} - c_{12}\, s_{13}\, s_{23}\, e^{i\delta_{\rm CP}} & c_{12}\, c_{23} - s_{12}\, s_{13}\, s_{23}\, e^{i\delta_{\rm CP}} & c_{13}\, s_{23} \\ s_{12}\, s_{23} - c_{12}\, s_{13}\, c_{23}\, e^{i\delta_{\rm CP}} & -c_{12}\, s_{23} - s_{12}\, s_{13}\, c_{23}\, e^{i\delta_{\rm CP}} & c_{13}\, c_{23} \end{pmatrix}$$

Table 14.7: 3ν oscillation parameters obtained from different global analyses of neutrino data. In all cases, the numbers labeled as NO (IO) are obtained assuming NO (IO), *i.e.*, relative to the respective local minimum. SK-ATM makes reference to the tabulated χ^2 map from the Super-Kamiokande analysis of their data in Ref. [97].

	Ref. [185] w/o SK-ATM		Ref. [185] w SK-ATM		Ref. [186] w SK-ATM		Ref. [187] w SK-ATM	
NO	Best Fit Ordering		Best Fit Ordering		Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.04^{+0.14}_{-0.13}$	$2.65 \to 3.46$	$3.20^{+0.20}_{-0.16}$	$2.73 \to 3.79$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.46^{+0.87}_{-0.88}$	$30.98 \to 36.03$	$34.5^{+1.2}_{-1.0}$	$31.5 \to 38.0$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$	$5.63^{+0.18}_{-0.24}$	$4.33 \to 6.09$	$5.51^{+0.19}_{-0.80}$	$4.30 \to 6.02$	$5.47^{+0.20}_{-0.30}$	$4.45 \to 5.99$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$47.9^{+1.1}_{-4.0}$	$41.0 \to 50.9$	$47.7^{+1.2}_{-1.7}$	$41.8 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$	$2.237^{+0.066}_{-0.065}$	$2.044 \to 2.435$	$2.14^{+0.09}_{-0.07}$	$1.90 \to 2.39$	$2.160^{+0.083}_{-0.069}$	$1.96 \to 2.41$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.41^{+0.18}_{-0.14}$	$7.9 \to 8.9$	$8.45^{+0.16}_{-0.14}$	$8.0 \to 8.9$
$\delta_{\rm CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	221^{+39}_{-28}	$144 \to 357$	238^{+41}_{-33}	$149 \to 358$	218^{+38}_{-27}	$157 \to 349$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.34^{+0.17}_{-0.14}$	$6.92 \to 7.91$	$7.55^{+0.20}_{-0.16}$	$7.05 \to 8.24$
$\frac{\Delta m^2_{32}}{10^{-3}\ {\rm eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$	$2.454^{+0.029}_{-0.031}$	$2.362 \to 2.544$	$2.419^{+0.035}_{-0.032}$	$2.319 \to 2.521$	2.424 ± 0.03	$2.334 \to 2.524$
IO	$\Delta\chi^2 = 6.2$		$\Delta\chi^2 = 10.4$		$\Delta\chi^2 = 9.5$		$\Delta\chi^2 = 11.7$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.03^{+0.14}_{-0.13}$	$2.64 \to 3.45$	$3.20^{+0.20}_{-0.16}$	$2.73 \to 3.79$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$	$33.40^{+0.87}_{-0.81}$	$30.92 \to 35.97$	$34.5^{+1.2}_{-1.0}$	$31.5 \to 38.0$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.63^{+0.19}_{-0.26}$	$4.30 \to 6.12$	$5.65^{+0.17}_{-0.22}$	$4.36 \to 6.10$	$5.57^{+0.17}_{-0.24}$	$4.44 \to 6.03$	$5.51^{+0.18}_{-0.30}$	$4.53 \to 5.98$
$\theta_{23}/^\circ$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$	$48.2^{+1.0}_{-1.4}$	$41.8 \to 50.9$	$47.9^{+1.0}_{-1.7}$	$42.3 \to 50.7$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.261^{+0.067}_{-0.064}$	$2.066 \to 2.461$	$2.259^{+0.065}_{-0.065}$	$2.064 \to 2.457$	$2.18^{+0.08}_{-0.07}$	$1.95 \to 2.43$	$2.220^{+0.074}_{-0.076}$	$1.99 \to 2.44$
$\theta_{13}/^\circ$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$	$8.49^{+0.15}_{-0.14}$	$8.0 \to 9.0$	$8.53^{+0.14}_{-0.15}$	$8.1 \to 9.0$
$\delta_{\rm CP}/^\circ$	285^{+24}_{-26}	$205 \to 354$	282^{+23}_{-25}	$205 \to 348$	247^{+26}_{-27}	$193 \to 346$	281^{+23}_{-27}	$202 \to 349$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.34^{+0.17}_{-0.14}$	$6.92 \to 7.91$	$7.55^{+0.20}_{-0.16}$	$7.05 \to 8.24$
$\frac{\Delta m^2_{32}}{10^{-3}\ {\rm eV}^2}$	$-2.509^{+0.032}_{-0.032}$	$-2.603 \to -2.416$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$	$-2.478^{+0.035}_{-0.033}$	$-2.577 \to -2.375$	$-2.50\pm^{+0.04}_{-0.03}$	$-2.59 \to -2.39$



PDG 2023

Neutrino Chiral Oscillation

In the SM neutrinos are produced by W and/or Z interactions.

At production $t=0$ point, they are left-handed and normalized, $\psi^h_L(0) = \sqrt{\frac{2E}{E-h\cdot p}}\frac{1-\gamma_5}{2}\psi^h(0)$.

$$\psi^h_L(t) = \sqrt{\frac{2E}{E-h\cdot p}}e^{-iHt}\frac{1-\gamma^5}{2}\psi^h(0) = \psi^h_L(t) = \sqrt{\frac{2E}{E-h\cdot p}}\left(e^{-iEt}\frac{1-\gamma_5}{2}\psi^h(0) - i\frac{m}{E}\sin(Et)\left[\beta, \frac{1-\gamma_5}{2}\right]\psi^h(0)\right).$$

Used
$$U(t) = e^{-iHt} = \cos(Et) - i\frac{\boldsymbol{\alpha}\cdot\mathbf{p} + m\beta}{E}\sin(Et)$$

$$\psi^{h\dagger}_L\psi^h_L(t) = \left(\cos(Et) + i\frac{h\cdot p}{E}\sin(Et)\right)e^{i\mathbf{p}\cdot\mathbf{L}}\ , \quad \psi^{h\dagger}_R\psi^h_L(t) = \left(-i\frac{m}{E}\sin(Et)\right)e^{i\mathbf{p}\cdot\mathbf{L}}$$

$$P(\nu^h_L \to \nu^h_L) = |\psi^{h\dagger}_L\psi^h_L(t)|^2 = 1 - \frac{m^2}{E^2}\sin^2(Et)\ , \quad P(\nu^h_L \to \nu^h_R) = |\psi^{h\dagger}_R\psi^h_L(t)|^2 = \frac{m^2}{E^2}\sin^2(Et)$$

Left-handed neutrinos oscillated into right-handed ones!

$$P(\nu^h_{Li} \to \nu^h_{Lk}) = |V_{ij}V^*_{kj}(\cos(E_jt) + i\frac{h\cdot p}{E_j}\sin(E_jt))|^2\ , \quad P(\nu^h_{Li} \to \nu^h_{Rk}) = |-iV_{ij}V^*_{kj}\frac{m_j}{E_j}\sin(E_jt)|^2\psi^{h\dagger}_R\psi^h_L(t)|^2$$

S-F Ge & P Pasquini, PLB811(2020)135961; V Bittencourt, A. Bernardini & M. Blasone, EPJC81 (2021)411.

Chiral oscillation probability extremely small for relativistic neutrinos because the suppresion factor: m^2/E^2.

Numerically vailid to use Dirac neutrinos to describe neutrino oscillations.

However the effect can be large for non-relativistic netrinos, such as background cosmic nutrinos where p is small compared with m.

S-F Ge & P Pasquini, PLB811(2020)135961; V Bittencourt, A. Bernardini & M. Blasone, EPJC81 (2021)411.

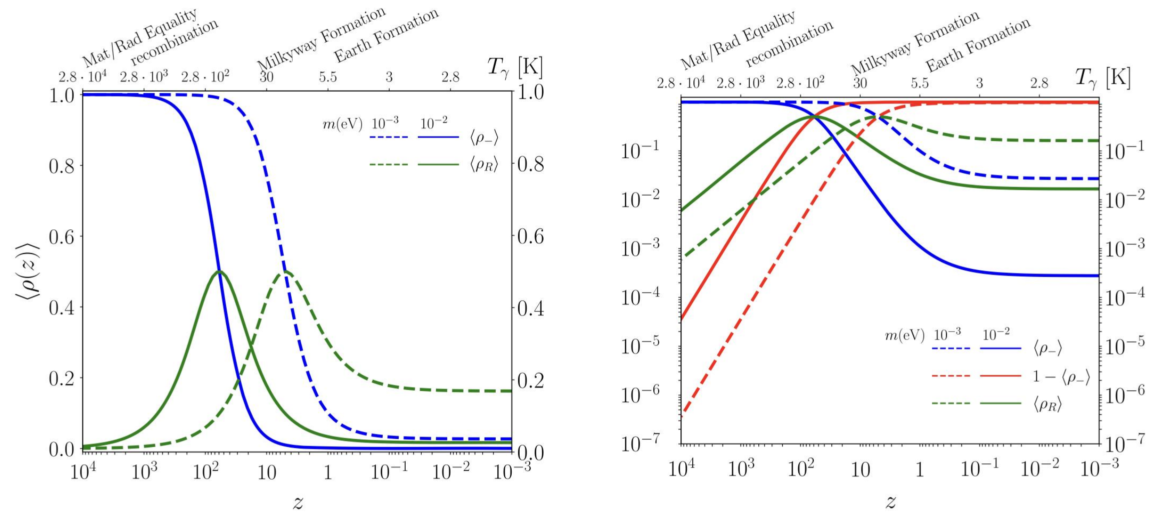
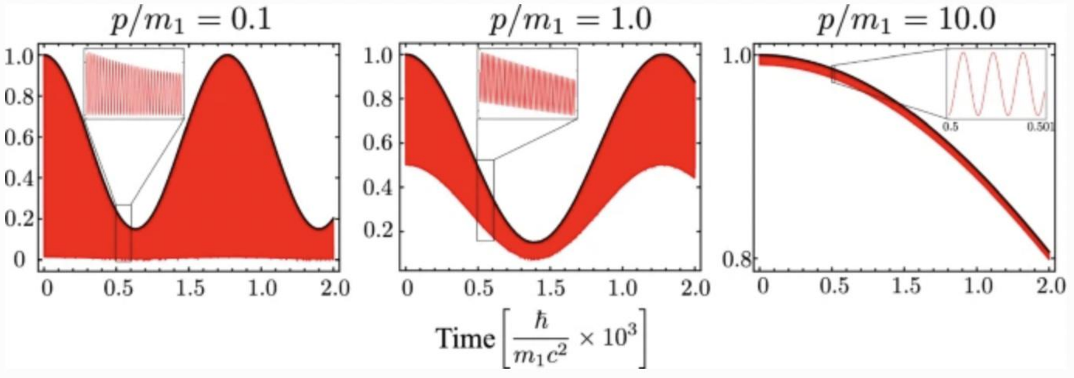


Fig. 1. Evolution of the chiral density matrix elements $\langle\rho_-\rangle$ (blue) or $1-\langle\rho_-\rangle$ (red), and $\rho_R = \mathbb{R}[c_L c_R^*]$ (green) as functions of the redshift z for $m = 10^{-2}$ eV (solid) and $m = 10^{-3}$ eV (dashed) with $|\mathbf{p}_d| = 1$ MeV. The redshift at neutrino decoupling is taken to be $z_d \sim 6 \times 10^9$.

Fig. 2



Survival probability $\mathcal{P}_{e\to e}(t)$ as a function of time. The black curves indicate the standard survival probability formula (16) and the red curves depict the full formula including the fast chiral oscillations (depicted in the insets). Parameters: $\sin^2\theta = 0.306$, $m_2^2 = \Delta_{21}^2 + m_1^2$, with $\Delta_{21}^2/m_1^2 = 0.01$

2. Neutrino Oscillation in Matter

When neutrinos travel in matter, due to interaction of neutrions with matter mediated by W and Z, the Lagrangian is modified

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi - j^\mu \bar{\psi}\gamma_\mu \frac{1-\gamma_5}{2}\psi \ .$$

j^μ is the matter current which neutrino can interact.
In the rest frame of the homogeneous, isotropic, unpolarized electrical neutrality medium, $j^\mu = (\rho, \vec{0})$
$\rho = \sqrt{2}G_F\left(N_e\delta_{\alpha e} - \frac{1}{2}N_n\right)$. N_e, N_n number density of electron and neutron, $\delta_{\alpha e}$ are zero for ν_μ and ν_τ.

$$\left(i\partial\!\!\!/ - m - \rho\gamma_0\frac{1-\gamma_5}{2}\right)\psi = 0 \qquad H = \mathbf{p}\cdot\boldsymbol{\alpha} + m\beta + \rho\frac{1-\gamma_5}{2} = \begin{pmatrix} \rho - \mathbf{p}\cdot\boldsymbol{\sigma} & m \\ m & \mathbf{p}\cdot\boldsymbol{\sigma} \end{pmatrix} = \begin{pmatrix} \rho - h\cdot p & m \\ m & h\cdot p \end{pmatrix}$$

The eigenvalues of H are: $E_1 = \frac{\rho}{2} + E_h$, $E_2 = \frac{\rho}{2} - E_h$, $E_h = \sqrt{m^2 + (h\cdot p - \rho/2)^2}$,

$$\psi_1 = \frac{1}{\sqrt{2E_h}}\begin{pmatrix} \sqrt{E_h - (h\cdot p - \frac{\rho}{2})}\, u^h \\ \sqrt{E_h + (h\cdot p - \frac{\rho}{2})}\, u^h \end{pmatrix} , \quad \psi_2 = \frac{1}{\sqrt{2E_h}}\begin{pmatrix} \sqrt{E_h + (h\cdot p - \frac{\rho}{2})}\, u^h \\ -\sqrt{E_h - (h\cdot p - \frac{\rho}{2})}\, u^h \end{pmatrix}$$

The evolution for a given wave function entering the media with momentum $\vec{p}$ at $t = 0$ is

$$\psi_L^h(t) = e^{-iHt}\psi_L^h(0) = e^{-\frac{i}{2}\rho t}\begin{pmatrix} \cos(E_h t) + i\frac{h\cdot p - \frac{\rho}{2}}{E_h}\sin(E_h t) & -i\frac{m}{E_h}\sin(E_h t) \\ -i\frac{m}{E_h}\sin(E_h t) & \cos(E_h t) - i\frac{h\cdot p - \frac{\rho}{2}}{E_h}\sin(E_h t) \end{pmatrix}\begin{pmatrix} u^h \\ 0 \end{pmatrix},$$

$$P(\psi_L^h \to \psi_L^h) = 1 - \frac{m^2}{E_h^2}\sin^2(E_h t)\ , \quad P(\psi_L^h \to \psi_R^h) = \frac{m^2}{E_h^2}\sin^2(E_h t).$$

Similar as that for free space, but dependent on matter density via $E_h = \sqrt{m^2 + (h\cdot p - \rho/2)^2}$.

There is a resonant enhanced chiral oscillation at $h \cdot p - \rho/2 = 0$!

Ultra-relativistic approximation for usual neutrino oscillation in matter

$$\rho/2 + \sqrt{m^2 + (h\cdot p - \rho/2)^2} \approx p + m^2/2p + \frac{1}{2}\rho(1 - \frac{h\cdot p}{p})\ .$$

Writing into matrix form before diagonolization of the mass matrix, the effective Hamiltonian is

$$H_{eff} = p + \frac{M^\dagger M}{2p} - \rho\frac{h\cdot p}{p}\ .$$

The same as the effective Hamiltonian for h=-1 by solving EOM with the same approximation.

3. Majorana and Seesaw Neutrinos in Free Space

Pure left-handed neutrinos, having Majorana mass like in Type II seesaw model

$$\mathcal{L} = \bar{\nu}_L i\partial\!\!\!/ \nu_L - \frac{1}{2} m \left(\bar{\nu}_L^c \nu_L + \text{h.c.}\right) - \bar{\nu}_L j_L^\mu \gamma_\mu \nu_L = \frac{1}{2} \bar{\psi}^m \left(i\partial\!\!\!/ - m\right) \psi^m - \bar{\psi}^m j^\mu \gamma_\mu \tfrac{1-\gamma_5}{2} \psi^m \quad , \quad \psi^m = \nu_L + \nu_L^c \, .$$

$$(i\partial\!\!\!/ - \widehat{M})\psi^m - j_L^\mu \gamma_\mu \tfrac{1-\gamma_5}{2} \psi^m + (j_L^\mu)^* \gamma_\mu \tfrac{1+\gamma_5}{2} \psi^m = 0 \, ,$$

$$\Rightarrow H = \boldsymbol{\alpha} \cdot \mathbf{p} + \beta m - \beta j_L^\mu \gamma_\mu (1-\gamma_5) = \begin{pmatrix} \rho - \mathbf{p}\cdot\boldsymbol{\sigma} & m \\ m & \mathbf{p}\cdot\boldsymbol{\sigma} - \rho \end{pmatrix} \, ,$$

ρ in the Dirac neutrino case is replaced by 2ρ.

$$U(t) = \begin{pmatrix} \cos(E_h^m t) + i\frac{h\cdot p - \rho}{E_h^m} \sin(E_h^m t) & -i\frac{m}{E_h^m} \sin(E_h^m t) \\ -i\frac{m}{E_h^m} \sin(E_h^m t) & \cos(E_h^m t) - i\frac{h\cdot p - \rho}{E_h^m} \sin(E_h^m t) \end{pmatrix}$$

where $E_h^m = \sqrt{m^2 + (h\cdot p - \rho)^2}$. Resonant point shifted to: $p - \rho = 0$.

$$P(\nu_L^h \to \nu_L^h) = \cos^2(E_h^m t) + \frac{(h\cdot p - \rho)^2}{(E_h^m)^2} \sin^2(E_h^m t) \, , \quad P(\nu_L^h \to (\nu_L^h)^c) = \frac{m^2}{(E_h^m)^2} \sin^2(E_h^m t)$$

One also obtains the same $H_{eff} = p + \frac{M^\dagger M}{2p} - h\cdot\rho$.

Seesaw Neutrino Oscillation

$$\mathcal{L} = \bar{\nu}_L i\partial\!\!\!/ \nu_L + \bar{N}_R i\partial\!\!\!/ N_R - \frac{1}{2}\left(\begin{pmatrix}\bar{\nu}_L^c & \bar{N}_R\end{pmatrix}\begin{pmatrix}M_L & M_D^T \\ M_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ N_R^c\end{pmatrix} + \text{h.c.}\right) = \bar{\psi}_L i\partial\!\!\!/ \psi_L - \frac{1}{2}\left(\bar{\psi}_L^c \mathcal{M}\psi_L + \text{h.c.}\right) \ ,$$

$$\psi_L = \begin{pmatrix}\nu_L \\ N_R^c\end{pmatrix} \ , \quad \mathcal{M} = \begin{pmatrix}M_L & M_D^T \\ M_D & M_R\end{pmatrix} \ ,$$

$$V^T\mathcal{M}V = \widehat{M} = \text{diag}\{m_1, m_2, m_3, M_1, M_2, M_3\} \ , \ \ \psi_L^m = V^\dagger \psi_L \ , \ \ \psi^m = \psi_L^m + (\psi_L^m)^c$$

$$\mathcal{L} = \bar{\psi}_L^m i\partial\!\!\!/ \psi_L^m - \frac{1}{2}\left((\bar{\psi}_L^m)^c \widehat{M}\psi_L^m + \text{h.c.}\right) = \frac{1}{2}\left(\bar{\psi}^m(i\partial\!\!\!/ - \widehat{M})\psi^m\right) \ ,$$

$$H = \begin{pmatrix}\boldsymbol{\alpha}\cdot\mathbf{p} + \widehat{M}_l\beta & 0 \\ 0 & \boldsymbol{\alpha}\cdot\mathbf{p} + \widehat{M}_h\end{pmatrix} \qquad ,$$

$$\widehat{M}_l = \text{diag}\{m_1, m_2, m_3\} \ , \ \widehat{M}_h = \text{diag}\{M_1, M_2, M_3\} \ .$$

The initial state would be

$$\psi_{Li}^h = \begin{pmatrix} V_{i1}^* \begin{pmatrix} u^h \\ 0 \end{pmatrix} \\ ... \\ V_{i6}^* \begin{pmatrix} u^h \\ 0 \end{pmatrix} \end{pmatrix} , \quad (\psi_{Li}^h)^c = \begin{pmatrix} V_{i1} \begin{pmatrix} 0 \\ u^h \end{pmatrix} \\ ... \\ V_{i6} \begin{pmatrix} 0 \\ u^h \end{pmatrix} \end{pmatrix} ,$$

$$U(t) = e^{-iHt}$$

$$= \begin{pmatrix} \begin{pmatrix} \cos(E_{m_1}t) + i\frac{h\cdot p}{E_{m_1}}\sin(E_{m_1}t) & -i\frac{m_1}{E_{m_1}}\sin(E_{m_1}t) \\ -i\frac{m_1}{E_{m_1}}\sin(E_{m_1}t) & \cos(E_{m_1}t) - i\frac{h\cdot p}{Em_1}\sin(E_{m_1}t) \end{pmatrix} & \cdots & 0 \\ \cdots & \cdots & \cdots \\ 0 & \cdots & \begin{pmatrix} \cos(E_{M_3}t) + i\frac{h\cdot p}{E_{M_3}}\sin(E_{M_3}t) & -i\frac{M_3}{E_{M_3}}\sin(E_{M_3}t) \\ -i\frac{M_3}{E_{M_3}}\sin(E_{M_3}t) & \cos(E_{M_3}t) - i\frac{h\cdot p}{E_{M_3}}\sin(E_3^M t) \end{pmatrix} \end{pmatrix}$$

$$E_{m_i} = \sqrt{p^2 + m_i^2} \ , \quad E_{M_i} = \sqrt{p^2 + M_i^2}$$

The oscillation probability

$$P(\psi^h_{Li} \to \psi^h_{Lj}) = \left|\psi^\dagger_{Lj} e^{-iHt} \psi_{Li}|^2\right|^2 = \left|\sum_k V_{ik} V^*_{jk} \left(\cos(E_k t) + i\frac{h \cdot p}{E_k} \sin(E_k t)\right)\right|^2$$

$$P(\psi^h_{Li} \to (\psi^h_{Lj})^c) = \left|(\psi^c_{Lj})^\dagger e^{-iHt} \psi_{Li}\right|^2 = \left|\sum_k V^*_{ik} V^*_{jk} \left(-i\frac{m_k}{E_k} \sin(E_k t)\right)\right|^2$$

$$P((\psi^h_{Li})^c \to (\psi^h_{Lj})^c) = \left|(\psi^c_{Lj})^\dagger e^{-iHt} \psi^c_{Lj}\right|^2 = \left|\sum_k V^*_{ik} V_{jk} \left(\cos(E_k t) - i\frac{h \cdot p}{E_k} \sin(E_k t)\right)\right|^2$$

$$P((\psi^h_{Li})^c \to \psi^h_{Lj}) = \left|\psi^\dagger_{Lj} e^{-iHt} \psi^c_{Lj}\right|^2 = \left|\sum_k V_{ik} V_{jk} \left(-i\frac{m_k}{E_k} \sin(E_k t)\right)\right|^2$$

Majorana phase effects on chiral oscillation

One light and one heavy example: $\widehat{M} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$, $V = \begin{pmatrix} V_{a1} & V_{a2} \\ V_{s1} & V_{s2} \end{pmatrix} = \begin{pmatrix} \cos\theta & e^{i\eta}\sin\theta \\ -\sin\theta & e^{i\eta}\cos\theta \end{pmatrix}$.

$$\nu_L^h = \begin{pmatrix} V_{a1}^* \begin{pmatrix} u^h \\ 0 \end{pmatrix} \\ V_{a2}^* \begin{pmatrix} u^h \\ 0 \end{pmatrix} \end{pmatrix} , \quad N_R^h = \begin{pmatrix} V_{s1} \begin{pmatrix} 0 \\ u^h \end{pmatrix} \\ V_{s2} \begin{pmatrix} 0 \\ u^h \end{pmatrix} \end{pmatrix} , \quad (\nu_L^h)^c = \begin{pmatrix} V_{a1} \begin{pmatrix} 0 \\ u^h \end{pmatrix} \\ V_{a2} \begin{pmatrix} 0 \\ u^h \end{pmatrix} \end{pmatrix} , \quad (N_R^h)^c = \begin{pmatrix} V_{s1}^* \begin{pmatrix} u^h \\ 0 \end{pmatrix} \\ V_{s2}^* \begin{pmatrix} u^h \\ 0 \end{pmatrix} \end{pmatrix} . \quad (2$$

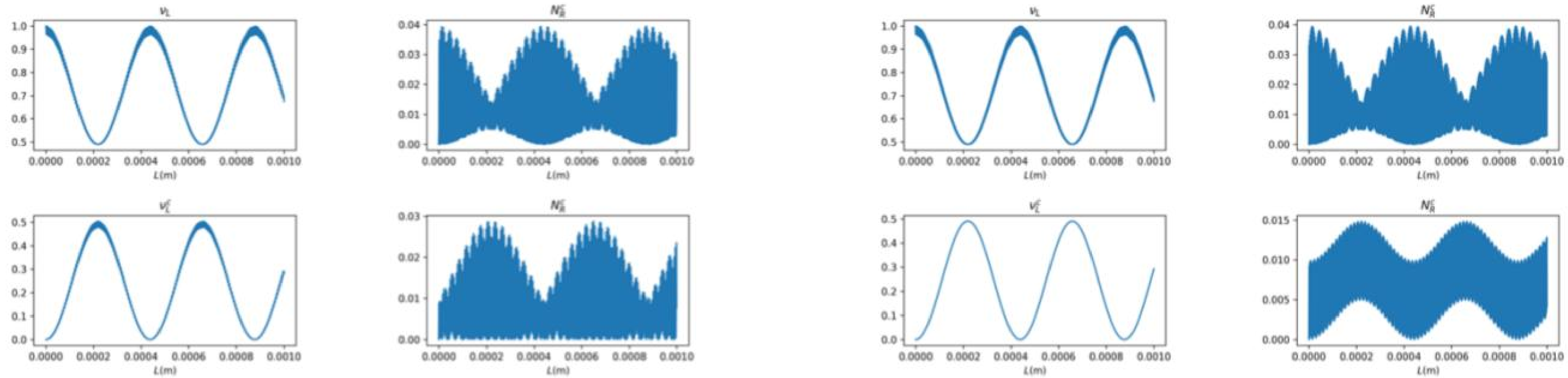
$$P(\nu_L^h \to \nu_L^h) = \left(\cos^2\theta\cos(E_m t) + \sin^2\theta\cos(E_M t)\right)^2 + p^2\left(\frac{\cos^2\theta}{E_m}\sin(E_m t) + \frac{\sin^2\theta}{E_M}\sin(E_M t)\right)^2$$

$$P(\nu_L^h \to (N_R^h)^c) = \frac{\sin^2 2\theta}{4}\left(\left(\cos(E_m t) - \cos(E_M t)\right)^2 + p^2\left(\frac{\sin(E_m t)}{E_m} - \frac{\sin(E_M t)}{E_M}\right)^2\right)$$

$$P(\nu_L^h \to (\nu_L^h)^c) = \frac{m^2}{(E_m)^2}\cos^4\theta\sin^2(E_m t) + \frac{mM}{2E_m E_M}\sin^2 2\theta\cos 2\eta\sin(E_m t)\sin(E_M t) + \frac{M^2}{(E_M)^2}\sin^4\theta\sin^2(E_M t)$$

$$P(\nu_L^h \to N_R^h) = \frac{\sin^2 2\theta}{4}\left(\frac{m^2}{(E_m)^2}\sin^2(E_m t) - \frac{2mM}{E_m E_M}\cos 2\eta\sin(E_m t)\sin(E_M t) + \frac{M^2}{(E_M)^2}\sin^2(E_M t)\right) .$$

Majorana phase show up in the chiral oscillation explicitly!
This also applies to Type II seesaw with two generations!



(a)$\eta = 0$ (b)$\eta = \frac{\pi}{4}$

FIG. 1: The oscillation between active neutrino and sterile neutrino in non-relativistic regime. The initial state is active neutrino. In this case, $p = 1\text{eV}$, $m = 10^{-3}\text{meV}$, and $\Delta m^2 = 1\text{eV}$, the mixing angle $\sin\theta = 0.1$, and the Majorana phase $\eta = 0, \frac{\pi}{4}$.

4. Majorana and Seesaw Neutrinos in Matter

The general seesaw neutrino Lagrangian in matter propagation

$$\mathcal{L} = \bar{\nu}_L i\partial\!\!\!/ \nu_L + \bar{N}_R i\partial\!\!\!/ N_R - \frac{1}{2}\left(\begin{pmatrix}\bar{\nu}^c_L & \bar{N}_R\end{pmatrix}\begin{pmatrix}M_L & M_D^T \\ M_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ N^c_R\end{pmatrix} + \text{h.c.}\right) - \begin{pmatrix}\bar{\nu}_L & \bar{N}^c_R\end{pmatrix}\begin{pmatrix}j^\mu_L & j^\mu_{RL} \\ j^{\mu\dagger}_{RL} & j_R\end{pmatrix}\gamma_\mu\begin{pmatrix}\nu_L \\ N^c_R\end{pmatrix}$$

$$= \bar{\psi}_L i\partial\!\!\!/ \psi_L - \frac{1}{2}\left(\bar{\psi}^c_L \mathcal{M}\psi_L + \text{h.c.}\right) - \bar{\psi}_L J^\mu \gamma_\mu \psi_L$$

For homogeneous, isotropic, unpolarized electrical neutrality matter medium at rest, only j^0_L is non-zero

$$j^0_L = \begin{pmatrix}\rho_e & 0 & 0 \\ 0 & \rho_\mu & 0 \\ 0 & 0 & \rho_\tau\end{pmatrix} = \begin{pmatrix}\sqrt{2}G_F\left(N_e - \frac{1}{2}N_n\right) & 0 & 0 \\ 0 & -\frac{G_F}{\sqrt{2}}N_n & 0 \\ 0 & 0 & -\frac{G_F}{\sqrt{2}}N_n\end{pmatrix}.$$

In terms of the mass eigenstate $\psi_L = V\psi^m_L$, the Lagrangian is

$$\mathcal{L} = \frac{1}{2}\left(\bar{\psi}^m(i\partial\!\!\!/ - \widehat{M})\psi^m\right) - \bar{\psi}^m \widetilde{J}^\mu \gamma_\mu \frac{1-\gamma_5}{2}\psi^m\,, \quad \psi^m = \psi^m_L + (\psi^m_L)^c\,, \quad \widetilde{J}^\mu = V^\dagger J^\mu V.$$

$$(i\partial\!\!\!/ - \widehat{M})\psi^m - \widetilde{J}^\mu\gamma_\mu\frac{1-\gamma_5}{2}\psi^m + (\widetilde{J}^\mu)^*\gamma_\mu\frac{1+\gamma_5}{2}\psi^m = 0\,.$$

$$H = \begin{pmatrix} \boldsymbol{\alpha}\cdot\mathbf{p} & 0 \\ 0 & \boldsymbol{\alpha}\cdot\mathbf{p} \end{pmatrix} + \begin{pmatrix} \beta\widehat{M}_l & 0 \\ 0 & \beta\widehat{M}_h \end{pmatrix} + V^\dagger \begin{pmatrix} j_L^\mu & j_{RL}^{\mu\dagger} \\ j_{RL}^\mu & -j_R^{\mu T} \end{pmatrix} V\gamma^0\gamma_\mu \tfrac{1-\gamma^5}{2} - \left(V^\dagger \begin{pmatrix} j_L^\mu & j_{RL}^{\mu\dagger} \\ j_{RL}^\mu & -j_R^{\mu T} \end{pmatrix} V\right)^* \gamma^0\gamma_\mu \tfrac{1+\gamma^5}{2}$$

Because the off-diagonal interaction, difficulty to get U(t). For just one light and one heavy neutrinos, can get a closed analytic expression.

Let $\widehat{M}_l = m$ and $\widehat{M}_h = M$, similar to Dirac case $j^\mu = (\rho, \vec{0})$ and $j_{RL}^\mu = j_R^\mu = 0$,

$$\widetilde{J}^\mu\gamma_\mu = V^\dagger J^\mu V\gamma_\mu = \begin{pmatrix} \frac{\rho}{2}(1+\cos 2\theta) & \frac{\rho}{2}e^{i\eta}\sin 2\theta \\ \frac{\rho}{2}e^{-i\eta}\sin 2\theta & \frac{\rho}{2}(1-\cos 2\theta) \end{pmatrix}\gamma_0 \,.$$

$$H = \begin{pmatrix} \frac{\rho}{2}(1+\cos 2\theta) - \mathbf{p}\cdot\boldsymbol{\sigma} & m & \frac{\rho}{2}e^{i\eta}\sin 2\theta & 0 \\ m & \mathbf{p}\cdot\boldsymbol{\sigma} - \frac{\rho}{2}(1+\cos 2\theta) & 0 & -\frac{\rho}{2}e^{-i\eta}\sin 2\theta \\ \frac{\rho}{2}e^{-i\eta}\sin 2\theta & 0 & \frac{\rho}{2}(1-\cos 2\theta) - \mathbf{p}\cdot\boldsymbol{\sigma} & M \\ 0 & -\frac{\rho}{2}e^{i\eta}\sin 2\theta & M & \mathbf{p}\cdot\boldsymbol{\sigma} - \frac{\rho}{2}(1-\cos 2\theta) \end{pmatrix}$$

The eigenvaluse of H are: $E_{1h} = -\sqrt{A_1 - A_2}\ , \quad E_{2h} = \sqrt{A_1 - A_2}\ ,$
$E_{3h} = -\sqrt{A_1 + A_2}\ , \quad E_{4h} = \sqrt{A_1 + A_2}\ ,$

$$A_1 = \frac{m^2 + M^2}{2} + \left(h \cdot p - \frac{\rho}{2}\right)^2 + \frac{\rho^2}{4}$$

$$A_2 = \sqrt{\frac{2\left(m^2 - M^2\right)^2 + \rho^2\left(2\left(m^2 + M^2 - 2mM\cos 2\eta\right)\sin^2\theta + 8\left(h \cdot p - \frac{\rho}{2}\right)^2\right) - 8\rho(m^2 - M^2)(h \cdot p - \frac{\rho}{2})\cos 2\theta}{8}}$$

$$U(t) = e^{-iHt} = \begin{pmatrix} U_{11} & U_{12} & U_{13} & U_{14} \\ U_{21} & U_{22} & U_{23} & U_{24} \\ U_{31} & U_{32} & U_{33} & U_{34} \\ U_{41} & U_{42} & U_{43} & U_{44} \end{pmatrix}$$

$$U_{12} = -\frac{i}{2}\left(\frac{m}{E_2}(1-A_6)\sin(E_2t) + \frac{m}{E_4}(1+A_6)\sin(E_4t)\right)$$
$$U_{21} = -\frac{i}{2}\left(\frac{m}{E_2}(1-A_6^*)\sin(E_2t) + \frac{m}{E_4}(1+A_6^*)\sin(E_4t)\right)$$
$$U_{43} = -\frac{i}{2}\left(\frac{M}{E_2}(1-B_6)\sin(E_2t) + \frac{M}{E_4}(1+B_6)\sin(E_4t)\right)$$
$$U_{34} = -\frac{i}{2}\left(\frac{M}{E_2}(1-B_6^*)\sin(E_2t) + \frac{M}{E_4}(1+B_6^*)\sin(E_4t)\right)$$
$$U_{31} = e^{-i\eta}\rho\sin 2\theta\left(\frac{(h\cdot p-\frac{\rho}{2})}{2A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) - \frac{i}{4}\Big(\frac{1-A_7}{E_2}\sin(E_2t) + \frac{1+A_7}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{13} = e^{i\eta}\rho\sin 2\theta\left(\frac{(h\cdot p-\frac{\rho}{2})}{2A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) - \frac{i}{4}\Big(\frac{1-A_7^*}{E_2}\sin(E_2t) + \frac{1+A_7^*}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{24} = e^{-i\eta}\rho\sin 2\theta\left(\frac{(h\cdot p-\frac{\rho}{2})}{2A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) + \frac{i}{4}\Big(\frac{1-A_7}{E_2}\sin(E_2t) + \frac{1+A_7}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{42} = e^{i\eta}\rho\sin 2\theta\left(\frac{(h\cdot p-\frac{\rho}{2})}{2A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) + \frac{i}{4}\Big(\frac{1-A_7^*}{E_2}\sin(E_2t) + \frac{1+A_7^*}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{23} = \rho\sin 2\theta\left(-\frac{(me^{i\eta}-Me^{-i\eta})}{4A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) - \frac{i}{2}\Big(\frac{A_8}{E_2}\sin(E_2t) - \frac{A_8}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{32} = \rho\sin 2\theta\left(-\frac{(me^{-i\eta}-Me^{i\eta})}{4A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) - \frac{i}{2}\Big(\frac{A_8^*}{E_2}\sin(E_2t) - \frac{A_8^*}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{41} = \rho\sin 2\theta\left(\frac{(me^{i\eta}-Me^{-i\eta})}{4A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) - \frac{i}{2}\Big(\frac{A_8}{E_2}\sin(E_2t) - \frac{A_8}{E_4}\sin(E_4t)\Big)\right)$$
$$U_{14} = \rho\sin 2\theta\left(\frac{(me^{-i\eta}-Me^{i\eta})}{4A_2}\Big(\cos(E_2t)-\cos(E_4t)\Big) - \frac{i}{2}\Big(\frac{A_8^*}{E_2}\sin(E_2t) - \frac{A_8^*}{E_4}\sin(E_4t)\Big)\right),$$

$$A_3 = \frac{m^2-M^2-2\rho\left(h\cdot p-\frac{\rho}{2}\right)\cos 2\theta}{2A_2},$$

$$A_4 = \frac{m^2-M^2+\rho^2}{2A_2}, \qquad A_5 = \frac{m^2-M^2+4\left(h\cdot p-\frac{\rho}{2}\right)^2}{2A_2},$$

$$B_4 = \frac{M^2-m^2+\rho^2}{2A_2}, \qquad B_5 = \frac{M^2-m^2+4\left(h\cdot p-\frac{\rho}{2}\right)^2}{2A_2}.$$

$$A_6 = \frac{4m(m^2-M^2)+(m-Me^{2i\eta})\rho^2-8m\left(h\cdot p-\frac{\rho}{2}\right)\rho\cos 2\theta-(m-Me^{2i\eta})\rho^2\cos 4\theta}{8mA_2}$$
$$B_6 = \frac{4m(M^2-m^2)+(M-me^{2i\eta})\rho^2+8M\left(h\cdot p-\frac{\rho}{2}\right)\rho\cos 2\theta-(M-me^{2i\eta})\rho^2\cos 4\theta}{8MA_2}$$
$$A_7 = \frac{m^2-2e^{2i\eta}mM+M^2+4\left(h\cdot p-\frac{\rho}{2}\right)^2}{2A_2}$$
$$A_8 = \frac{(me^{i\eta}+Me^{-i\eta})\left(h\cdot p-\frac{\rho}{2}\right)+\frac{\rho}{2}(me^{i\eta}-Me^{-i\eta})\cos 2\theta}{2A_2}.$$

$$U_{11} = \frac{1}{2}\Big((1-A_3)\cos(E_2t)+(1+A_3)\cos(E_4t)\Big) + i\left(\frac{(\pm 2p-\rho)(1-A_4)-\rho(1-A_5)\cos 2\theta}{E_2}\sin(E_2t) + \frac{(\pm 2p-\rho)(1+A_4)-\rho(1+A_5)\cos 2\theta}{E_4}\sin(E_4t)\right)$$
$$U_{22} = \frac{1}{2}\Big((1-A_3)\cos(E_2t)+(1+A_3)\cos(E_4t)\Big) - i\left(\frac{(\pm 2p-\rho)(1-A_4)-\rho(1-A_5)\cos 2\theta}{E_2}\sin(E_2t) + \frac{(\pm 2p-\rho)(1+A_4)-\rho(1+A_5)\cos 2\theta}{E_4}\sin(E_4t)\right)$$
$$U_{33} = \frac{1}{2}\Big((1-A_3)\cos(E_2t)+(1+A_3)\cos(E_4t)\Big) + i\left(\frac{(\pm 2p-\rho)(1-B_4)-\rho(1-B_5)\cos 2\theta}{E_2}\sin(E_2t) + \frac{(\pm 2p-\rho)(1+B_4)-\rho(1+B_5)\cos 2\theta}{E_4}\sin(E_4t)\right)$$
$$U_{44} = \frac{1}{2}\Big((1-A_3)\cos(E_2t)+(1+A_3)\cos(E_4t)\Big) - i\left(\frac{(\pm 2p-\rho)(1-B_4)-\rho(1-B_5)\cos 2\theta}{E_2}\sin(E_2t) + \frac{(\pm 2p-\rho)(1+B_4)-\rho(1+B_5)\cos 2\theta}{E_4}\sin(E_4t)\right)$$

$$P(\nu_L^h \to \nu_L^h) = \left|(\nu_L^h)^\dagger e^{-iHt}\nu_L^h\right|^2 = \left|U_{11}\frac{1+\cos 2\theta}{2} + U_{13}e^{-i\eta}\frac{\sin 2\theta}{2} + U_{31}e^{i\eta}\frac{\sin 2\theta}{2} + U_{33}\frac{1-\cos 2\theta}{2}\right|^2$$

$$P(\nu_L^h \to (N_R^h)^c) = \left|((N_R^h)^c)^\dagger e^{-iHt}\nu_L^h\right|^2 = \left|-U_{11}\frac{\sin 2\theta}{2} - U_{13}e^{-i\eta}\frac{1-\cos 2\theta}{2} + U_{31}e^{i\eta}\frac{1+\cos 2\theta}{2} + U_{33}\frac{\sin 2\theta}{2}\right|^2$$

$$P(\nu_L^h \to (\nu_L^h)^c) = \left|((\nu_L^h)^c)^\dagger e^{-iHt}\nu_L^h\right|^2 = \left|U_{21}\frac{1+\cos 2\theta}{2} + U_{23}e^{-i\eta}\frac{\sin 2\theta}{2} + U_{41}e^{-i\eta}\frac{\sin 2\theta}{2} + U_{43}e^{-2i\eta}\frac{1-\cos 2\theta}{2}\right|^2$$

$$P(\nu_L^h \to N_R^h) = \left|(N_R^h)^\dagger e^{-iHt}\nu_L^h\right|^2 = \left|-U_{21}\frac{\sin 2\theta}{2} - U_{23}e^{-i\eta}\frac{1-\cos 2\theta}{2} + U_{41}e^{-i\eta}\frac{1+\cos 2\theta}{2} + U_{43}e^{-2i\eta}\frac{\sin 2\theta}{2}\right|^2$$

η enters the chiral oscillation, even when time averaged!

Massive neutrinos can have chiral oscillation, supressed by m^2/E^2 for relativistic neutrinos, but the supression is lefted for non-relativisitc neutrions.

Majorana phases modify the oscillatin pattern. In principle Majorana phases can be probed in chiral oscillation.

When matter effects are included, energies are splitted into two, there is a resoant point for chiral oscillation. Also even the oscillation is time aberaged, Majorana phase still affect oscillatin pattern.

Thank you for your attentions