Insight into neutrino mass phenomenology by exploring non-relativistic oscillations in quantum field theory

広島大学 CORE-U LIPI

新学術「地下宇宙」2021年領域研究会

Nicholas J. Benoit†, A. S. Adam‡, Y. Kawamura†, Y. Matsuo†, T. Morozumi†, Y. Shimizu‡, and N. Toyota

†Graduate School of Science, Hiroshima University; ‡Graduate School of Advanced Science and Engineering, Hiroshima University; ‡Research Center for Physics, Indonesian Institute of Sciences (LIPI)

Introduction

- From experiments neutrinos experience flavor oscillations
  - This leads to massive neutrinos, which are beyond the SM

$$m^2_{\nu 2} - m^2_{\nu 1} \simeq 7.42 \times 10^{-5}\text{eV}^2 \qquad |m^2_{\nu 3} - m^2_{\nu 2}| \simeq 2.517 \times 10^{-3}\text{eV}^2$$

- Massive neutrinos are allowed two types of mass
  - Determination of the mass type is an important goal in physics

Dirac mass or Majorana mass	
$\overline{\nu}_R m_D \nu_L$	$\frac{1}{2} m_M \overline{(\nu_L)^c} \nu_L$

- Massive neutrinos can also be ordered two different ways
  - Neutrino mass ordering is an interesting phenomenon

Normal hierarchy or Inverted hierarchy	
$m_1 < m_2 \ll m_3$	$m_3 \ll m_1 < m_2$

- An interesting application includes low energy neutrinos
  - Example: Cosmic Neutrino Background (CνB) $T_\nu \simeq 1.676 \times 10^{-4}$eV

Methods

We introduce a novel QFT formulation of unified neutrino oscillations. We consider the situation where the produced neutrinos are part of the weak interaction SU(2) doublet and carry a lepton number based on the doublet flavor.

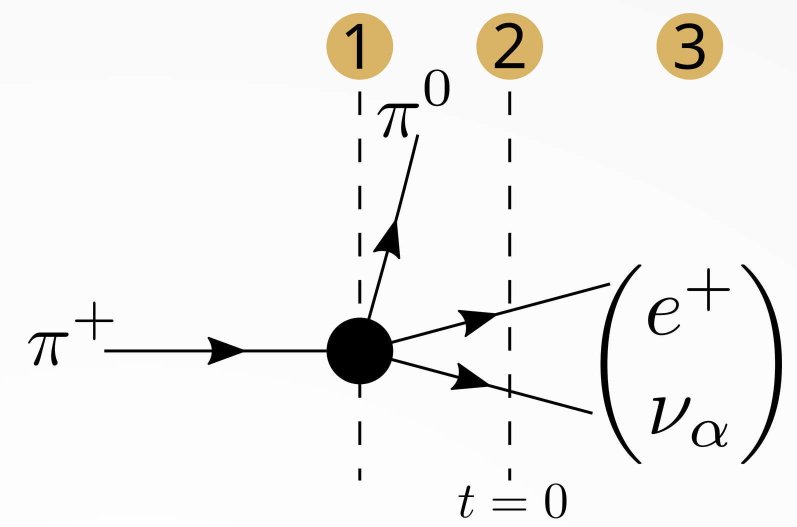

Figure 1. The neutrino's flavor is determined at positron creation (1). Then the neutrino acquires mass at (2). Lastly, the lepton number evolves (3).

We describe this process with the Lagrangians.

Majorana Lagrangian

$$\mathcal{L}^M = \overline{\nu}_L i\gamma^\mu \partial_\mu \nu_L - \theta(t)\left(\frac{m_M}{2}\overline{(\nu_L)^c}\nu_L + \text{h.c.}\right)$$

Dirac Lagrangian

$$\mathcal{L}^D = \overline{\nu}_L i\gamma^\mu \partial_\mu \nu_L + \overline{\nu}_R i\gamma^\mu \partial_\mu \nu_R - \theta(t)\left(\overline{\nu}_R m \nu_L + \text{h.c.}\right)$$

Then, after some time the neutrino acquires mass. At which point the evolution of the lepton number is modified by new mass dependent terms. We define the neutrino's lepton number as such,

$$L_\alpha = \int d^3x \bar{\nu}_\alpha \gamma^0 \nu_\alpha$$

Lastly, we prepare a flavor vacuum to study the expectation value of the evolving lepton number.

References: ※ A. S. Adam, etc.; *PTEP*, ptab025, arXiv:2101.07751 [hep-ph] https://doi.org/10.1093/ptep/ptab025

Results

We find differences related to the type of mass and mass hierarchy are enhanced when the neutrinos are *non-relativistic*. We illustrate the differences in Fig.2 by using the neutrino parameters from Nu-Fit v5.0 (2020) data.

Mass Differences

For the Majorana case, the expecation value is not conserved.

Majorana Non-conservation

$$\sum_\alpha \langle \mathbf{q}, \sigma | L^M_\alpha(t) | \mathbf{q}, \sigma \rangle = 1 - 2\sum_i |V_{\sigma i}|^2 \left(\frac{m_i}{E_i}\right)^2 \sin^2(E_i t)$$

However, the values are constrained between -1 and 1.

Majorana Limits

$$-1 \leq \sum_i |V_{\sigma i}|^2 \frac{|\mathbf{q}|^2 - m_i^2}{|\mathbf{q}|^2 + m_i^2} \leq \sum_\alpha \langle \mathbf{q}, \sigma | L^M_\alpha(t) | \mathbf{q}, \sigma \rangle \leq 1$$

For the Dirac case, the expecation value is conserved.

Dirac Conservation

$$\sum_\alpha \langle \mathbf{q}, \sigma_L | L^L_\alpha(t) | \mathbf{q}, \sigma_L \rangle + \sum_\alpha \langle \mathbf{q}, \sigma_L | L^R_\alpha(t) | \mathbf{q}, \sigma_L \rangle = 1$$

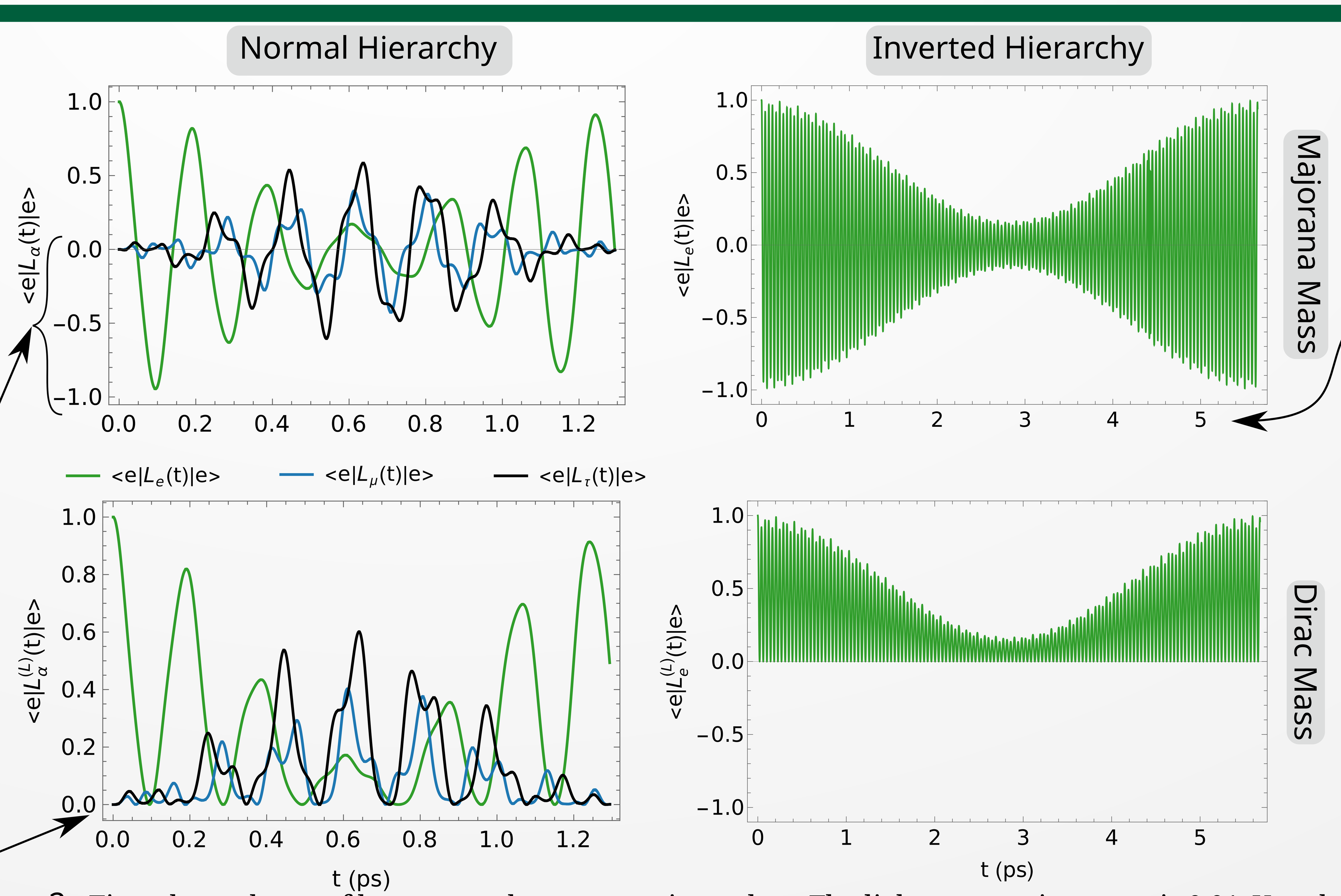

Figure 2. Time dependence of lepton number expectation value. The lightest neutrino mass is 0.01eV and their momentum is 0.0002eV, meaning all the neutrinos are non-relativistic. The Majorana phases are zero.

Hierarchy Differences

Change of mass hierarchy cause differences in the amplitudes and periods of oscillations.

This is because in the *non-relativistic* region terms similar to below become important,

$$\left(1 - \frac{q^2}{E_i(q)E_j(q)}\right)\cos([E_i(q) + E_j(q)]t)$$

Enhanced in *non-relativisic*

These terms have are senstive to the absolute masses of the neutrinos.