Neutrino Oscillations as Vacuum Multi-refringence

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Based on:
Markku Oksanen, Nico Stirling, & Anca Tureanu. Neutrino flavour waves through the quantum vacuum: A theory of oscillations. Physics Letters B, 865, 139461, arXiv: 2411.14348

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Motivation

Standard neutrino oscillation theory assumes:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i(m_i)\rangle \qquad m_i \neq m_j \text{ for } i \neq j$$

, where

But, this is **inconsistent** with quantum theory due to **superselection rules**:

$m_i \neq m_j$ ...then $\langle \nu_i(m_i)|\hat{\mathcal{O}}|\nu_j(m_j)\rangle = 0 \quad \forall \hat{\mathcal{O}}$, if holds that

Then $|\nu_i(m_i)\rangle$ and $|\nu_j(m_j)\rangle$ belong to different **superselection sectors**

And therefore their **coherent superpositions** are **not allowed**

Our Approach

1. **Massless flavour neutrinos** are the only physical particle states.

1. The **Lagrangian mass terms** are treated as **interactions** which induces **coherent forward scattering** during propagation in vacuum.

1. **Multiple coherent forward scattering** leads to a **coherent wave** which experiences **multi-refringence.**

1. The coherent wave gives the **probability amplitude** for neutrino oscillations.

1. The **feebleness** of the "mass aivina" interaction **iustifies** treating neutrinos as massless in weak interactions: $\tau_m^\nu \sim 10^8 \text{ years} \gg \tau_W \sim 10^{-8} \text{ s}$

Details

1. Production

- Definite flavour
- Definite energy
- Definite momentum
- Massless: $E = |\mathbf{p}|$

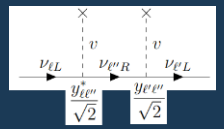
Propagation

Assuming
- Dirac neutrinos
- Higgs mechanism

$$\mathcal{L}_{\text{int}} = -\bar{\nu}_{\ell' L}(x) M_{\ell'\ell} \nu_{\ell R}(x) + h.c.$$

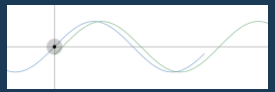
where $M_{\ell'\ell} = \frac{y_{\ell'\ell} v}{\sqrt{2}}$

2. Coherent forward scattering:



Scattering amplitude

$$f_{\ell'\ell}(0) = -\frac{V}{2\pi}(MM^\dagger)_{\ell'\ell}$$



Phase kicks at each scattering
Energy, momentum not changed

Multiple scattering:

$$\sum_\ell \left[(\nabla^2 + E^2)\delta_{\ell'\ell} + 4\pi N f_{\ell'\ell}(0)\right]\Psi_{\nu_\ell}(\mathbf{x}, t) = 0$$

Detection

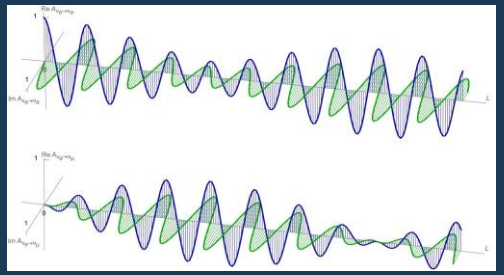
Standard Oscillation Probabilities:

$$P_{\nu_\ell \to \nu_{\ell'}} = |\Psi_{\nu_{\ell'}}|^2$$

Coherent Neutrino Wave Properties

$$\Psi_{\nu_{\ell'}}(\mathbf{x},t) = e^{-i(Et-\bar{n}\mathbf{p}\cdot\mathbf{x})} \sum_{i,\ell} U_{\ell' i} U^*_{\ell i} e^{\frac{i}{F}\sum_{ij}\Delta n_{ij}\mathbf{p}\cdot\mathbf{x}} \Psi_{\nu_\ell}(\mathbf{0},0)$$

1. Multicomponent complex wave with modulated amplitude



2. Universal group velocity and effective refractive mass

$$v_g = \frac{1}{\frac{1}{F}\sum_{i=1}^{F}\left(1-\frac{m_i^2}{E^2}\right)^{-1/2}}, \qquad m^2_{\text{refr}} = \overline{m^2}$$

3. Evanescence $E < \min(m_i) \implies \overline{n}$ imaginary

Key Results

Theoretical advantages

- Describing **flavour oscillation** without resorting to different mass superpositions.
- **Coherence** is manifest throughout production, propagation and detection.
- Well defined **speed**, **energy** and **momentum** of oscillating neutrinos.

Phenomenology

- Prediction of **zero mass** in weak decay kinematics (KATRIN, Project 8)
- Prediction for neutrino **time of flight** based on unique group velocity.
- No decoherence induced by wave packet separation due to unique group velocity of wave.
- **Low energy** neutrino **evanescence** due to mass being a refractive effect.

Thank you!

Poster + happy to discuss at any time

References

This work:

1. M. Oksanen, N. Stirling, & A. Tureanu (2025). Neutrino flavour waves through the quantum vacuum: A theory of oscillations. Physics Letters B, 865, 139461. arXiv: 2411.14348

More on neutrino oscillations and multi-refringence:

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3. A. Tureanu (2025). On massive neutrinos and coherence in neutrino oscillations. Nuclear Physics B, 1018, 117052.
4. S. F. Ge, C. F. Kong and A. Y. Smirnov (2024). Testing the Origins of Neutrino Mass with Supernova-Neutrino Time Delay. Phys. Rev. Lett. 133 no.12, 121802. arXiv:2404.17352

Multiple scattering framework:

4. L. L. Foldy (1945). The Multiple Scattering of Waves. Physics Reviews, 67, 107.
5. M. Lax (1951). Multiple Scattering of Waves. Reviews of Modern Physics, 23, 287.

Superselection rules: