

Contribution ID: **166** Type: **Parallel Talk**

Exact and Hybrid Probabilities of Neutrino Oscillations in a Uniform Medium

Monday, 30 November 2026 16:10 (30 minutes)

We examine the oscillations between three neutrino flavors propagating in matter of constant density, using the evolution operator combined with the Lagrange interpolation formula and Vieta's identities of the Hamiltonian. This gives us exact, closed-form expressions for Pee, Pμe, and Pμτ that are compact and structurally identical to their vacuum counterparts. Each probability is a sum of terms weighted by coefficients that depend on matter only through the eigenvalues and elements of the Hamiltonian matrix. CP violation appears as a single term proportional to the Jarlskog invariant J. No mixing angles or CP phase are required in matter, clearly separating genuine CP violation from matter-induced effects. We explicitly verify that when the potential vanishes, our formulas reduce to those for the vacuum. Since exact eigenvalues involve non-illuminating trigonometric expressions, We complement our study with a hybrid approach, in which, in the expressions of the exact probabilities, the exact eigenvalues are replaced by the approximate ones expressed in terms of radicals, which are obtained by two successive rotations of the Hamiltonian. The resulting probabilities are exactly unity for any choice of eigenvalues. For a DUNE-like setup, they reproduce the exact results with absolute errors less than 2×10^{-6} in all channels, for both neutrinos and antineutrinos.

Academic position of the presenting author

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Session Classification: Parallel Talks-SD:704

Track Classification: Neutrinos