Snowmass LOI: Direct Probes of the Matter Effect in Neutrino Oscillations

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The Standard Model Wolfenstein matter effect plays a crucial role in neutrino oscillations and our ability to understand the mass ordering as well as measure CP violation. Despite the importance of this process for the future oscillation program, it is not yet well constrained by measurements. Comparisons between next-generation experiments both with and without the matter effect are vital to ensure the robustness of oscillation results.

Frontiers: Primary: NF01 and TF11. Secondary: NF02, NF03, NF05

Standard Model Matter Effect: The matter effect is a process by which neutrinos and antineutrinos in the electron state experience a potential due to the forward elastic charged current scattering off electrons [1]. There is also a neutral current potential, but this affects all active flavors equally so it does not lead to any relative phase accumulation and thus plays no role in three flavor oscillations. This process is the primary driver for DUNE's strong sensitivity to the mass ordering and has a strong effect on the measurement of CP violation. Thus it is crucial that we have a precise constraint on the matter effect. DUNE should be able to measure this at the $\sim 30\%$ level [2] and T2HK/T2HKK can provide some additional information [3]. A consistent measurement of the atmospheric mass splitting both with (DUNE [4]) and without (JUNO [5]) the matter effect is essential to ensure the robustness of any results leveraging the matter effect.

In addition to long-baseline-accelerator experiments, the matter effect also plays a large role in both regular solar neutrinos and the day-night effect. By comparing solar measurements with data from KamLAND one can constrain the matter effect. While the measurements of solar oscillation parameters are consistent [6–8], the uncertainties from solar experiments are quite large. Improved measurements of solar neutrinos from DUNE and Hyper-KamiokaNDE [9, 10] can improve this. Meanwhile, KamLAND measurements will be further improved at JUNO [5].

Steriles: The matter effect is also important for sterile neutrino oscillations. Since sterile neutrinos don't experience the neutral current process, there is an effective matter potential for sterile neutrinos $\sim \frac{1}{2}$ that for electron neutrinos [11–16]. This is leveraged by IceCube to place strong constraints on sterile neutrinos with $\Delta m^2_{41} \sim 1$ eV^2 [17, 18]. A detection of sterile neutrinos by IceCube via the active-sterile resonance, if confirmed by other experiments, would also be a detection of the neutral current component of the matter effect.

Supernovae: The dynamics of supernovae are governed by neutrino physics with neutrino-neutrino interactions playing a significant role. This process is related to the standard matter effect governing long-baseline and solar neutrino oscillations.

Connection to NSI: The Standard Model matter effect is connected to neutrino non-standard interactions (NSI) [1, 19]. NSIs provide a simple effective field theory means of relating new physics between neutrinos and matter particles (usually electrons, up quarks, and down quarks) to oscillation physics. In principle the ϵ_{ee} term in this framework (see e.g. [19] for more on the NSI framework) is directly related to the matter effect. Most constraints on ϵ_{ee} assume interactions with quarks only. Thus the constraints on ϵ_{ee} tend to be a bit stronger than directly on the matter effect as comparisons between solar neutrinos and terrestrial neutrinos provide additional information since the up- to down-quark ratio is quite different in each environment. Nonetheless, global oscillation fits to NSIs show that ϵ_{ee} is the poorest constrained NSI parameter with $\sim \mathcal{O}(100\%)$ uncertainty [20, 21]. While this does not directly translate into a constraint on the matter effect it should be close at the order-of-magnitude level.

Summary: The Standard Model matter effect plays a crucial role in our capability to measure the mass ordering and CP violation. Thus it is crucial to verify that it works as anticipated. Current data provides only poor constraints, mostly from solar data. Next generation experiments, notably DUNE and Hyper-K, will significantly leverage the matter effect and thus can constrain the matter effect via a comparison to other experiments with less matter effect such as JUNO.

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