Neutrino Oscillations

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Context

In 1930, Wolfgang Pauli proposed the existence of the neutrino based on observations of nuclear beta decay (1). 25 years after, neutrinos were detected by Fred Reines and Clyde Cowan. In 1962 was discovered the muon neutrino, ν_μ and later in 2000, DONUT discovered the tau neutrino ν_τ. The theory of three types of neutrinos suggests that each neutrino type, ν_e, ν_μ, and ν_τ, defined by the way it interacts, is a mixture of three mass eigenstates, ν_1, ν_2, and ν_3. This idea originated in 1962 with Maki, Nakagawa, and Sakata. Now, using QM we can obtain an equation for N generation neutrino oscillation probability $P_{\nu_\alpha \to \nu_\beta}$[1]:

$$= \delta^\alpha_\beta - 4\sum_{i>j}^{N} \mathrm{Re}[A] \sin^2 \frac{(E_i - E_j)\,t}{2} - 2\sum_{i>j}^{N} \mathrm{Im}[A] \sin(E_i - E_j)\,t \quad (1)$$

Where $\alpha = e, \mu, \tau, \ldots$ correspond to flavour basis and $i = 1, 2, \ldots, N$ to mass eigenbasis. $A \equiv U_{\beta}{}^{j}\,(U^\dagger)_j{}^{\alpha} U^{*\beta}{}_i\,(U^\top)^i{}_\alpha$ and U is the unitary mixing matrix also called PMNS matrix.

Atmospheric neutrinos

Atmospheric neutrinos are produced in hadronic showers resulting from collisions of cosmic rays with nuclei in the upper atmosphere. Production of electron and muon neutrinos is dominated by the processes $\pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ (and their charge conjugates).

If 100% $\mu^\pm$ decay before reaching the detector then we have a $2\nu_\mu : 1\nu_e$ ratio. At Super-Kamiokande there was found a zenith angle dependent deficit of muon neutrinos that could be explained with two-flavor $\nu_\mu \leftrightarrow \nu_\tau$ oscillations[2]. For $N = 2$ the survival probability is:

$$P_{a\to b} = 1 - \sin^2 2\theta \sin^2 \frac{1.269\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]} \quad (2)$$

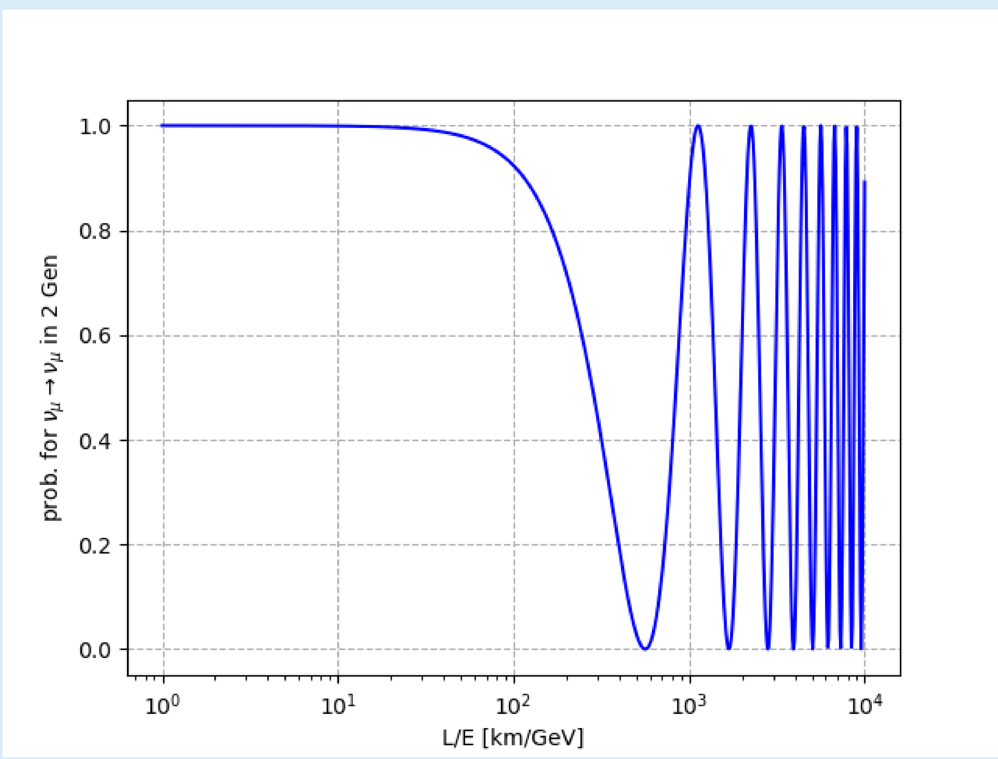


Figure: Oscillation probability Eq. (2) for $\nu_\mu \to \nu_\mu$ in vacuum with $N = 2$ as a function of L/E. Parameters: $\Delta m^2 = 2.2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta = 1.0$.

Reactor neutrinos

Nuclear fission reactors produce energy from β decays $n \to p + e^- + \bar{\nu}_e$.[3] There are two categories of reactor neutrino experiments according to the baseline length: #1 Short baseline $L \sim$ km [4][5] and #2 long baseline $L \sim 100$ km[6]. The baseline lengths are determined by the mass-squared differences with which expect the oscillation signals.

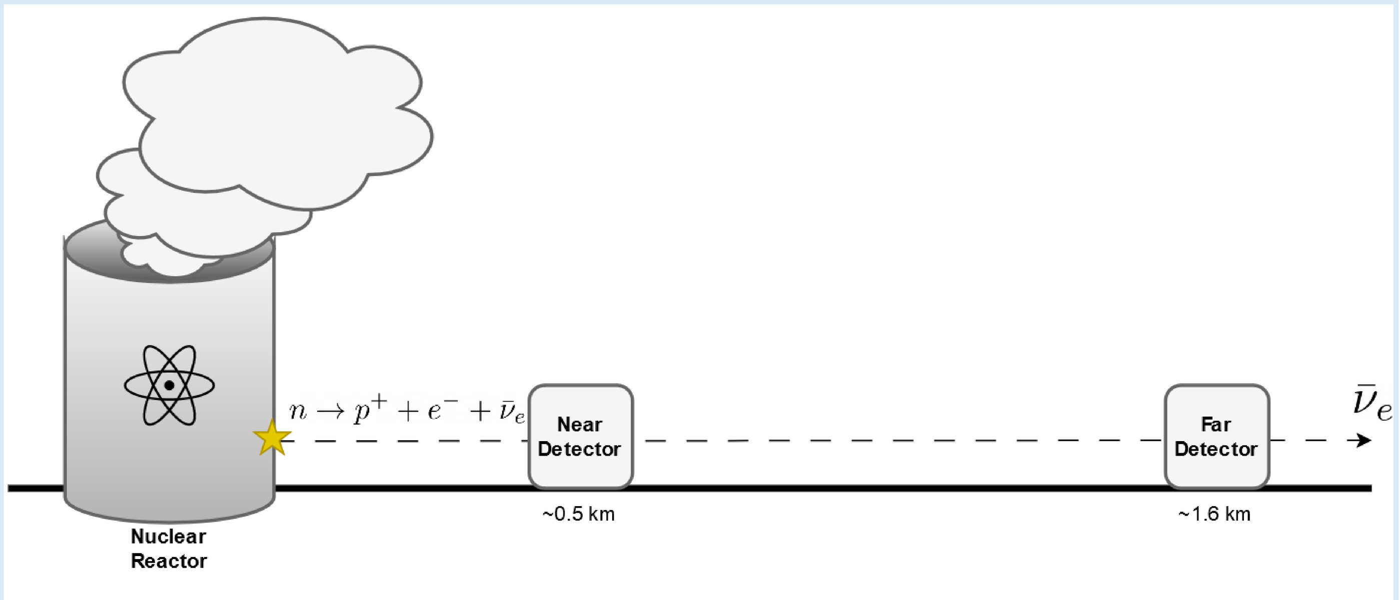
In DayaBay it was discovered a decrease of $\bar{\nu}_e$ flux at their far detectors which can be understood with the 2-generation oscillation formula with the mass-square difference Δm^2_{31} and mixing angle θ_{13}.

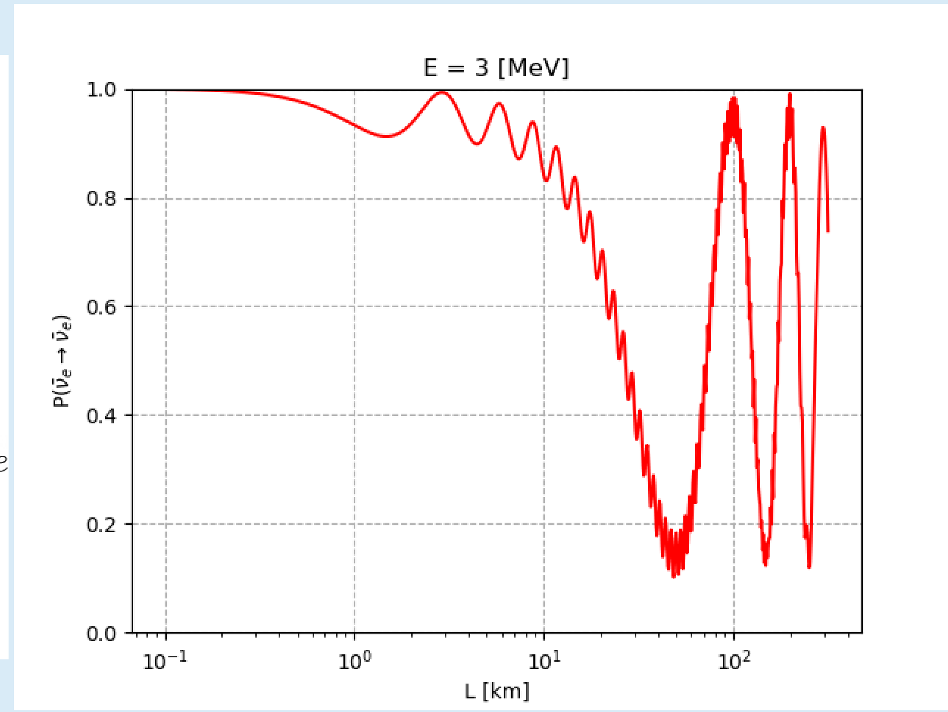
In short baseline $\frac{\Delta m^2_{21} L}{4E} \ll 1$ and $\Delta m^2_{31} \simeq \Delta m^2_{32}$. Then we have $P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$.

In long-baseline $\frac{\Delta m^2_{31} L}{4E} \gg 1$ then $P_{\bar{\nu}_e \to \bar{\nu}_e} = \sin^4\theta_{13} + \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}\right]$.

For $N = 3$ and PMNS matrix the equation with no approximations is:

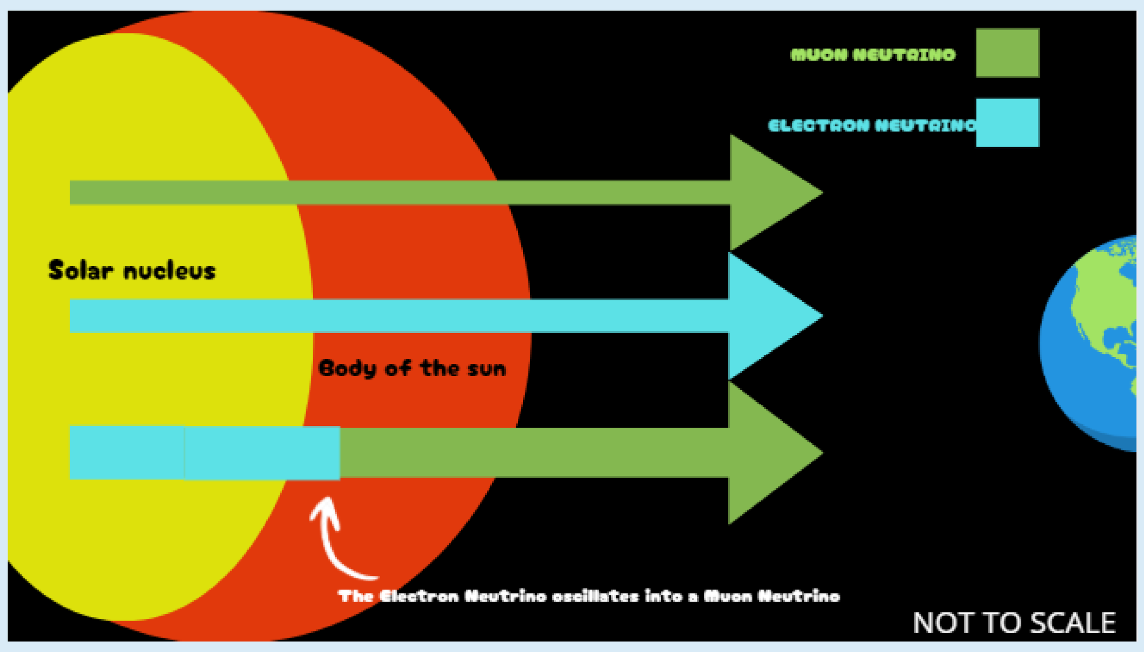
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - 4|U_e^1|^2|U_e^2|^2 \sin^2 \frac{\Delta m^2_{21} L}{4E} - 4|U_e^1|^2|U_e^3|^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} - 4|U_e^2|^2|U_e^3|^2 \sin^2 \frac{\Delta m^2_{32} L}{4E} \quad (3)$$

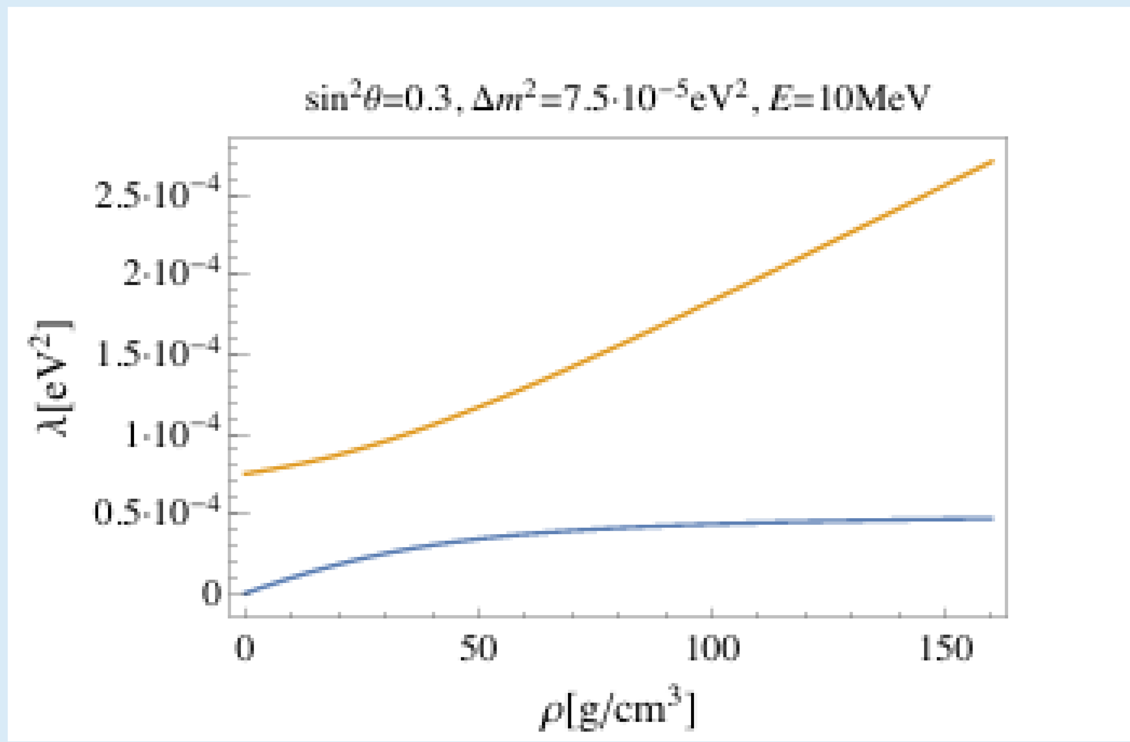




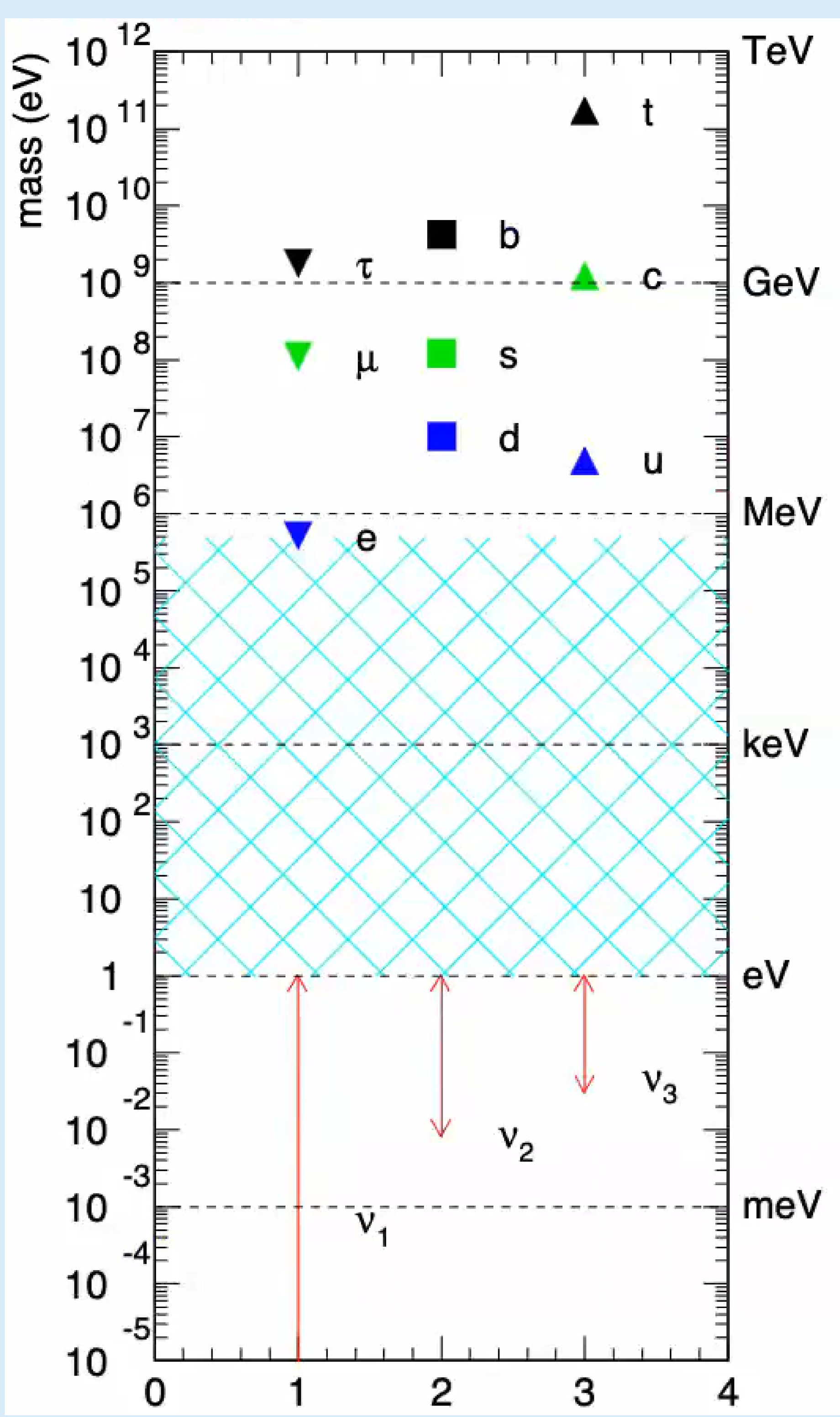
Solar neutrinos

The core of the sun produces neutrinos due to fusion process. But when we meassure the solar neutrino flux we had less than a half of the predicted by the standar model. In 1985 Mikheyev and Smirnov points out that due to an adiabatic conversion process, the flavour of electron neutrino could change. Then in 2002, the data released by SNO, showed that the number of solar electron neutrino was smaller than the expected by the Standar model, but the total number of neutrinos was consistent with the theory, then, the electron neutrino are converted into muon and tau neutrinos.





Research Today



NEUTRINOS HAVE MASS!
ALL EXPERIMENTAL RESULTS ARE CONSISTEN IN 3 GENERATION ν FRAMEWORK!
BUT... we still have questions the standar model for particle physics cannot explain, for example:

1. What is dark matter?
2. Why is so much ordinary matter in the Universe?
3. Why does the universe appear to be accelerating?
4. Why does it appear that the universe underwent rapid acceleration in the past?

We think neutrinos may have the answer we are searching for, and people are working on it. Specifically in neutrino masses there is:

- Minimal RH Neutrino
  - Long-lived scalars
  - with Higgs portal
  - from ERS
- Discrete Symmetries

References

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