HOW MUCH DOES MSW CONTRIBUTES TO THE REACTOR ANTINEUTRINO ANOMALY?

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Abstract

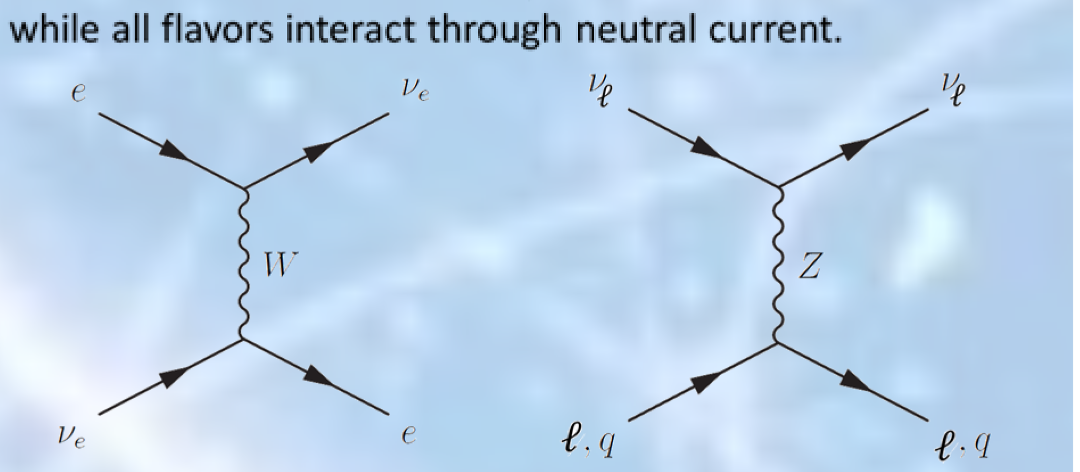
It has been pointed out that there is a $5.7 \pm 2.3\%$ discrepancy between the predicted and the observed reactor antineutrino flux in very short baseline experiments. Several causes for this anomaly have been discussed, including a possible non-standard forth neutrino. In order to quantify how much "non-standard" this anomaly really is, the standard MSW effect is here revisited. Knowing that reactor antineutrinos are produced in a very dense medium, ultra-non-adiabatic effects may take place changing the neutrino survival probability, decreasing the observed flux just outside the reactor.

Motivation

Although neutrino interactions with matter are feeble (the mean free path of low energy neutrinos on lead is of the order of a light-year), matter can still affect neutrinos trough coherent scattering, what is called MSW effect. On Earth based neutrino sources this can be almost always neglected since it depends on the density of the surroundings, which varies between 1 and 4g/cm^3 in the Earth's crust. On the other hand, it is the major effect to be considered on solar neutrinos since the Sun's core density varies from 150 to 160g/cm^3. But the dependence of the MSW effect on neutrinos is not just related to the concentration of matter, but also with how much it changes along the way. Abrupt changes lead to what is called Non-Adiabatic effects that have strong influences on the oscillation pattern, enhancing or suppressing the survival probability of a given neutrino flavor. This is exactly what happens with reactors antineutrinos: they are created inside the nuclear fuel rods, which are as dense as 18g/cm^3, and immediately leave to water. From their ultra-relativistic reference frame they observe an almost discontinuous change on the surroundings, what could in principle lead to very strong effects. Of course, no strong change on the vacuum oscillation pattern is observed, raising the questions: How much does the MSW effect contributes to the so called reactor antineutrino anomaly? Does it contribute at all, and if so, could it explain the observed deficit?

The MSW Effect

When not propagating in vacuum, the Hamiltonian that describes the neutrino state evolution must consider a contribution from the weak potential where each possible interaction (i.e. charged or neutral current) have its own potential. These contributions, although coming from the interaction Lagrangian, do not represent real interactions: we assume that the only two interaction points in the history of a neutrino are its creation and its detection. Nevertheless, the mere possibility of these interactions corresponds to phase changes in the neutrino state, without destroying the coherence. Moreover, each component of the neutrino state is affected differently since only (anti)electron neutrinos can interact through charged current (since there are no μ or τ on the environment), while all flavors interact through neutral current.



Since neutral currents contributes globally, it does not affects the oscillation probability and the effective Schrödinger equation (in 2ν approximation) if given by:

$$i\frac{d}{dx}\begin{pmatrix}\tilde{\nu}_1\\ \tilde{\nu}_2\end{pmatrix}_{\tilde{m}} = \begin{pmatrix}\frac{\tilde{m}_1^2}{2E} & -i\frac{d\tilde{\theta}}{dx}\\ i\frac{d\tilde{\theta}}{dx} & \frac{\tilde{m}_2^2}{2E}\end{pmatrix}\begin{pmatrix}\tilde{\nu}_1\\ \tilde{\nu}_2\end{pmatrix}_{\tilde{m}} \quad (1)$$

expressed here in the mass base. The "tilde" ~ sign indicates the dependence with the surrounding matter, which in turn reflects on both the mixing angle and the masses.

The effective mixing $\tilde{\theta}(x)$ and squared mass difference $\Delta\tilde{m}^2(x)$ are given by:

$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - a)^2 + \sin^2 2\theta}} \quad (2)$$

and

$$\Delta\tilde{m}^2 = \Delta m^2\left(\frac{\sin 2\theta}{\sin 2\tilde{\theta}}\right) \quad (3)$$

and the weak potential is represented by the a factor:

$$a = \pm\frac{\sqrt{2}G_F\, E_\nu\, n_e(x)}{\Delta m^2} \quad (4)$$

where G_F is the Fermi constant, E_ν is the neutrino energy and $n_e(x)$ electron number density of the surrounding environment. The plus and minus signs corresponds to neutrino and antineutrino respectively (considering the potential generated by ordinary matter). For neutrinos, eq. (2) has the shape of a Breit-Wigner resonance, with maximum at $\cos 2\theta = a$ and width at half-height $\sin 2\theta$. Fig. 1 shows an example considering the solar mixing $\sin 2\theta_{12} = (0.857 \pm 0.025)$.

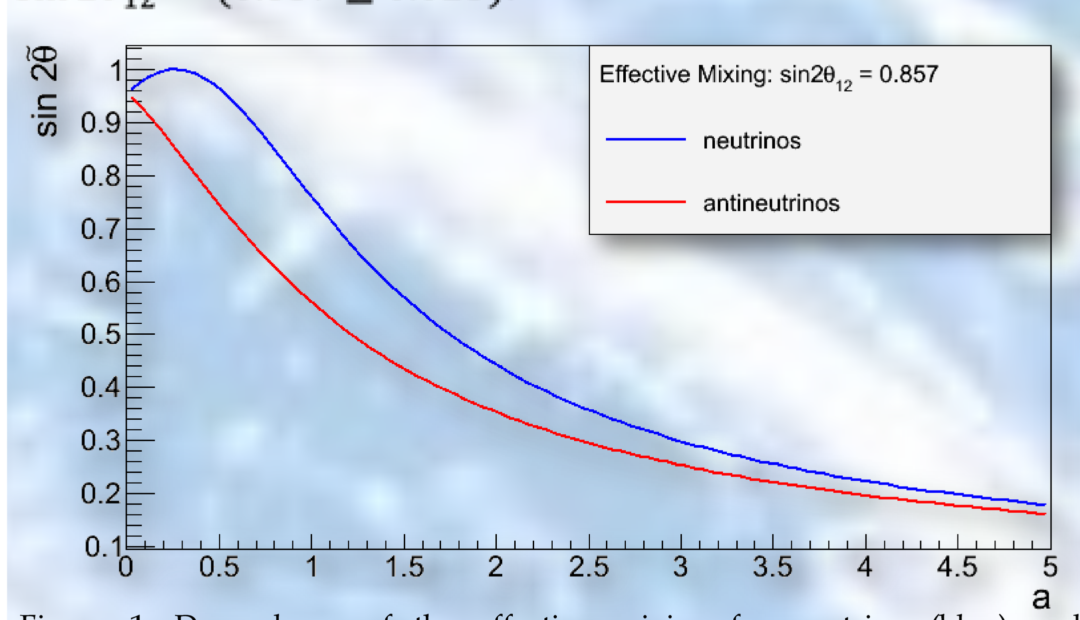


Figure 1: Dependence of the effective mixing for neutrino (blue) and antineutrino (red) traveling through ordinary matter.

From eq. (5) one can see that the strength of the effect comes mainly from the relation between $\sqrt{2}G_F\, E_\nu\, n_e$ and Δm^2. Since our interest is on reactor antineutrinos, we are dealing with low energy and low densities. Knowing that $\Delta m_{12}^2 = 7.50 \times 10^{-17}$MeV and $\Delta m_{23}^2 \cong \Delta m_{13}^2 = 2.32 \times 10^{-15}$MeV, any effect coming from the 1-3 scale is highly suppressed (while no effect is expected from the 2-3 since both $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ interact equally).

Decompression and Level Crossing

From eq. (1) one can see that there are two cases of concern: (i) when the density is constant, the effective Hamiltonian is:

$$H_{(i)} = -\frac{\Delta\tilde{m}^2}{4E_\nu}\sigma_z \quad (5)$$

and (ii) when the density changes abruptly:

$$H_{(ii)} = \frac{d\tilde{\theta}}{dx}\sigma_y \quad (6)$$

where σ_z and σ_y are Pauli matrices. Integrating eq. (1) with the Hamiltonian (5) leads to the usual oscillation pattern. On the other hand, integrating (1) with (6) gives a discrete change in the neutrino state:

$$\nu' = e^{i\Delta\tilde{\theta}\sigma_y}\nu \quad (7)$$

This change contributes mostly when the neutrino created inside the fuel rod leaves for a less dense medium causing a ***decompression*** due to abrupt change on the effective mixing angle $\Delta\tilde{\theta}(a \to b) = \tilde{\theta}_b - \tilde{\theta}_a$.

This effect will also take place when the neutrino crosses several rods of nuclear fuel in its way out of the reactor. This ***level crossing*** effect have no influence here since the neutrino faces a succession of $\Delta\tilde{\theta}$ and $-\Delta\tilde{\theta}$ changes for each crossing, canceling them out. As a result, the neutrino state evolution and the consequent survival probability can be expressed only in terms of the first change on mixing after creation (decompression) and the combination of the total path traveled inside the nuclear fuel and on vacuum, giving:

$$\begin{aligned}P_{ee} &= \cos^4\Delta\tilde{\theta} + \sin^2\Delta\tilde{\theta}\sin^2\Sigma\tilde{\theta}\\ &\quad + \left(\cos^2\Delta\tilde{\theta} - \cos^2\Sigma\tilde{\theta}\right)\sin^2\alpha\\ &\quad + \frac{1}{4}\sin 2\Sigma\tilde{\theta}\sin^2 2\Delta\tilde{\theta}\ \sin 2\alpha\end{aligned} \quad (8)$$

where $\Delta\tilde{\theta} = \theta - \tilde{\theta}_{fuel}$, $\Sigma\tilde{\theta} = \theta + \tilde{\theta}_{fuel}$ and

$$\alpha = \frac{\Delta m^2}{4E_\nu}\left(L_{\text{reactor}} + L_{\text{baseline}}\right) \quad (9)$$

where $L_{\text{baseline}}$is the usual reactor-detector distance and L_{reactor} is a characteristic distance related to the reactor geometry and composition, with values roughly of the order of the reactor dimensions.

Eq. (8) shows that even for $\alpha = 0$, $P_{ee} < 1$. Since $\tilde{\theta}$ is a function of the neutrino energy E_ν, the exact value of $P_{ee}(\alpha = 0)$ is shown on Fig. 2.

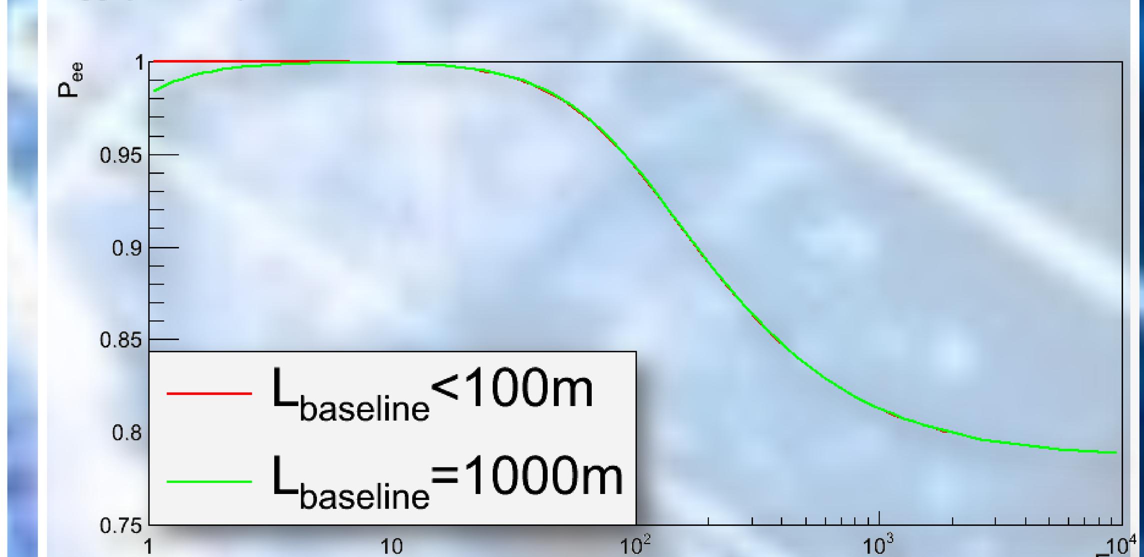


Figure 2: Survival probability for electron antineutrinos, considering a very short baseline (red) and a kilometer baseline (green).

The analysis shows that no deviation from unit is expected for very short baselines ($L_{\text{baseline}} \leq 100$m). On the other hand, for baselines of the order of 1000m it is expected a deficit of about 2% for neutrinos with energy of the order of 1MeV.

Conclusion

This is the report of a work in progress. Using just the standard MSW effect it is possible to explain up to 2% of the reactor antineutrino anomaly that has observed. The era of high precision neutrino physics has began and delivers the need for we to reevaluate the precision of our models predictions if we want to explore more exotic solutions.