The Three Neutrino Scenario

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I have discussed in my talk several remaining issues in the standard three-flavor mixing scheme of neutrinos, in particular, the sign of Δm^2_{13} and the leptonic CP violating phase. In this report I focus on two topics: (1) supernova method for determining the former sign, and (2) illuminating how one can detect the signatures for both of them in long-baseline ($\gtrsim$ 10 km) neutrino oscillation experiments. I do this by formulating perturbative frameworks appropriate for the two typical options of such experiments, the high energy and the low energy options with beam energies of $\sim$ 10 GeV and $\sim$ 100 MeV, respectively.

1. INTRODUCTION

Despite the current trend that many people jumped into the four neutrino scheme (see [1] for comprehensive references), the three-flavor mixing scheme of leptons, together with the three-flavor mixing scheme of quarks, still constitutes the most promising standard model for the structure of the (known to date) most fundamental matter in nature. It is worth to note that the two of the evidences for the neutrino oscillation, one compelling [2] and the other strongly indicative [3], can be nicely fit into the three-flavor mixing scheme of neutrinos. I want to call the scheme the standard 3 ν mixing scheme in my talk.

I would like to address in this talk some aspects of the three-flavor mixing scheme of neutrinos which remain to be explored untill now. While I have started with a brief remark on robustness of the standard 3 ν mixing scheme, I do not repeat it here because I have described it elsewhere [4]. In this manuscript I discuss mainly two key issues, (1) the sign of Δm^2_{13}, and (2) how to measure leptonic CP violation. I will use, throughout this manuscript, the MNS matrix [5] in the convention by Particle Data Group.

Let me start by raising the following question; "Suppose that the standard 3 ν mixing scheme is what nature exploits and the atmospheric and the solar neutrino anomalies are the hints kindly provided by her to lead us to the scheme. Then, what is left toward our understanding of its full structure?"

It is conceivable that the future atmospheric and solar neutrino observations as well as currently planned long baseline experiments will determine four parameters, Δm^2_{23}, Δm^2_{12}, θ_{23}, and θ_{12}, to certain accuracies. I then cite four things as in below which will probably be unexplored in the near future:
(i) θ_{13}
(ii) the sign of $\Delta m^2_{13} \equiv m^2_3 - m^2_1$, the normal versus inverted mass hierarchies
(iii) the CP violating leptonic Kobayashi-Maskawa phase δ
(iv) the absolute masses of neutrinos

I make brief comments on (i) and (iv) one by one before focusing on (ii) and (iii):

Measuring θ_{13} is one of the goals of the currently planned long baseline experiments [6–8], and therefore I do not discuss it further. Among them the expected sensitivity in JHF, the recently approved experiment in Japan, is one of the best examined case [9].

Measuring absolute masses of neutrinos is certainly the ultimate challenge for neutrino experiments, but it is not clear at this moment how one can do it. Presumably, neutrinoless double β

decay experiments are the most promising. We, however, do not discuss it further, but just recommend the interested readers to look into a report at this conference [10].

2. SIGN OF Δm^2_{13}

Nunokawa and I recently discussed [4,11] that the features of neutrino flavor transformation in supernova (SN) is sensitive to the sign of $\Delta m^2_{13} \equiv m^2_3 - m^2_1$, making contrast between the normal ($\Delta m^2_{13} > 0$) vs. inverted ($\Delta m^2_{13} < 0$) mass hierarchies. Therefore, one can obtain insight on the sign of Δm^2_{13} by analyzing neutrino events from supernova. With use of the unique data at hand from SN1987A [12], we have obtained a strong indication that the normal mass hierarchy, $m_3 \gg m_1 \sim m_2$, is favored over the inverted one, $m_1 \sim m_2 \gg m_3$.

The point is that there are always two MSW resonance points in SN for neutrinos with cosmologically interesting mass range, $m_\nu \lesssim 100$ eV. The higher density point, which I denote the H resonance, plays a deterministic role. If the H resonance is adiabatic the feature of ν flavor transformation in SN is best characterized as $\nu_e - \nu_{heavy}$ exchange, as first pointed out in Ref. [13]. Here, ν_{heavy} collectively denotes ν_μ and ν_τ, which are physically indistinguishable in SN. See also Ref. [14] for a recent complehensive treatment of 3 ν flavor conversion in SN.

Now the question is: how does the sign of Δm^2_{13} make difference? The answer is: if Δm^2_{13} is positive (negative) the neutrino (antineutrino) undergoes the resonance. Then, if the inverted mass hierarchy is the case and assuming the adiabaticity of H resonance, the $\bar{\nu}_e$ which to be observed in terrestrial detectors comes from original $\bar{\nu}_{heavy}$ in neutrinosphere. It is widely recognized that, due to their weaker interactions with surrounding matter, ν_{heavy} and $\bar{\nu}_{heavy}$ are more energetic than ν_e and $\bar{\nu}_e$. Since the $\bar{\nu}_e$ induced CC reaction is the dominant reaction channel in water Cherenkov detectors, the effect of such flavor transformation would be sensitively probed by them.

We draw in Fig. 1 equal likelihood contours as a function of the heavy to light ν temperature ratio $\tau \equiv T_{\bar{\nu}_x}/T_{\bar{\nu}_e} = T_{\nu_x}/T_{\bar{\nu}_e}$ on the space spanned by $\bar{\nu}_e$ temperature and total neutrino luminosity by giving the neutrino events from SN1987A. The data comes from Kamiokande and IMB experiments [12]. In addition to it we introduce an extra parameter η defined by $L_{\nu_x} = L_{\bar{\nu}_x} = \eta L_{\nu_e} = \eta L_{\bar{\nu}_e}$ which describes the departure from equipartition of energies to three neutrino species and examine the sensitivity of our conclusion against the change in η.

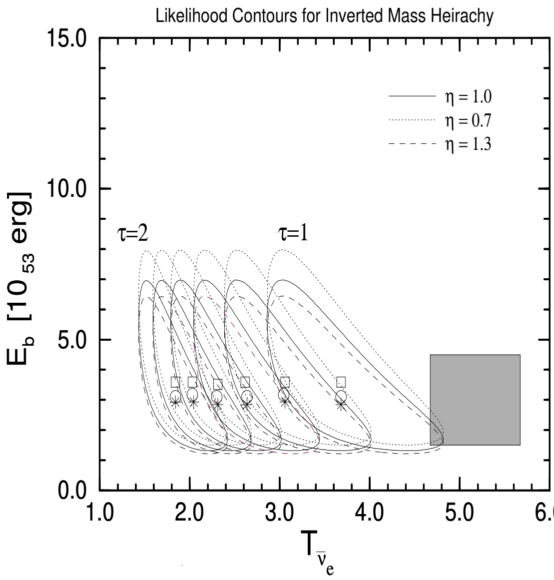

Fig.1: Contours of constant likelihood which correspond to 95.4 % confidence regions for the inverted mass hierarchy under the assumption of adiabatic H resonance. From left to right, $\tau \equiv T_{\bar{\nu}_x}/T_{\bar{\nu}_e} = T_{\nu_x}/T_{\bar{\nu}_e} = 2, 1.8, 1.6, 1.4, 1.2$ and 1.0 where $x = \mu, \tau$. Best-fit points for $T_{\bar{\nu}_e}$ and E_b are also shown by the open circles. The parameter η parametrizes the departure from the equipartition of energy, $L_{\nu_x} = L_{\bar{\nu}_x} = \eta L_{\nu_e} = \eta L_{\bar{\nu}_e}$ ($x = \mu, \tau$), and the dotted lines (with best fit indicated by open squares) and the dashed lines (with best fit indicated by stars) are for the cases $\eta = 0.7$ and 1.3, respectively. Theoretical predictions from supernova models are indicated by the shadowed box.

At $\tau = 1$, that is at equal $\bar{\nu}_e$ and ν_e temperatures, the 95 % likelihood contour marginally overlaps with the theoretical expectation [15] represented by the shadowed box in Fig. 1. When the temperature ratio τ is varied from unity to 2 the likelihood contour moves to the left, indicating less and less consistency between the standard theoretical expectation and the observed feature of the neutrino events. This is simply because the observed energy spectrum of $\bar{\nu}_e$ must be interpreted as that of the original one of $\bar{\nu}_{heavy}$ in the presence of the MSW effect in $\bar{\nu}$ channel. It implies that the original $\bar{\nu}_e$ temperature must be lower by a factor of τ than the observed one, leading to stronger inconsistency at larger τ.

The solid lines in Fig. 1 are for the case of equipartition of energy into three flavors, $\eta = 1$, whereas the dotted and the dashed lines are for $\eta = 0.7$ and 1.3, respectively. We observe that our result is very insensitive against the change in η.

We conclude that if the temperature ratio τ is in the range 1.4-2.0 as the SN simulations indicate, the inverted hierarchy of neutrino masses is disfavored by the neutrino data of SN1987A unless the H resonance is nonadiabatic, i.e., unless $s^2_{13} \lesssim$ a few $\times 10^{-4}$ [4,11].

3. HOW TO MEASURE SIGN OF Δm^2_{13} AND CP VIOLATION IN NEUTRINO OSCILLATION EXPERIMENTS ?

The possibility that SN can tell about the sign of Δm^2_{13} is, I think, interesting and in fact it is the unique available hint on the question at this moment. We, the authors of Ref. [11], feel that our argument and the analysis done with the SN1987A data is reasonably robust. But, of course, it would be much nicer if we can have independent confirmation by terrestrial experiments. With regard to the CP violating effect mentioned in (iii) it appears, to my understanding, that the best place for its measurement is long ($\gtrsim$ 10 km) baseline neutrino oscillation experiments.

We develop an analytic method by which we can explore various regions of experimentally variable parameters to illuminate at where CP violating effects are large and how one can avoid serious matter effect contamination. Actually we formulate below a perturbative framework to have a bird-eye view of at where the sign of Δm^2_{13} is clearly displayed and the CP violating phase manifests itself. Some of the earlier attempts to formulate perturbative treatment to explore the verious regions may be found in [16].

We rewrite the Schrödinger equation by using the basis $\tilde{\nu}$ defined by (Γ is a CP phase matrix) $\tilde{\nu_\alpha} = \left[e^{-i\lambda_5\theta_{13}}\Gamma^+_\delta e^{-i\lambda_7\theta_{23}}\right]_{\alpha\beta}\nu_\beta$, into the form

$$i\frac{\mathrm{d}}{\mathrm{d}x}\tilde{\nu_\alpha} = (H)_{\alpha\beta}, \tilde{\nu_\beta} \tag{1}$$

where Hamiltonian H contains the following three terms:

$$H = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{\Delta_{13}}{2E} \end{bmatrix} + a(x)\begin{bmatrix} c^2_{13} & 0 & c_{13}s_{13} \\ 0 & 0 & 0 \\ c_{13}s_{13} & 0 & s^2_{13} \end{bmatrix} + \frac{\Delta_{12}}{2E}\begin{bmatrix} s^2_{12} & c_{12}s_{12} & 0 \\ c_{12}s_{12} & c^2_{12} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2}$$

We first note the order of magnitude of a relevant quantity to observe the hierarchies of various terms in the Hamiltonian:

$$\frac{\Delta m^2}{E} = 10^{-13}\left(\frac{\Delta m^2}{10^{-3}\mathrm{eV}^2}\right)\left(\frac{E}{10\mathrm{GeV}}\right)^{-1}\mathrm{eV}. \tag{3}$$

It may be compared with the matter potential $a(x) = \sqrt{2}G_F N_e(x)$ where N_e denotes electron number density in the earth;

$$a(x) = 1.04 \times 10^{-13}\left(\frac{\rho}{2.7\mathrm{g/cm}^3}\right)\left(\frac{Y_e}{0.5}\right)\mathrm{eV}, \tag{4}$$

where $Y_e \equiv N_p/(N_p+N_n)$ is the electron fraction.

In view of these results one can identify two typical cases, the high and low energy options with ν beam energies $\sim$ 10 GeV and $\sim$ 100 MeV, respectively, each with a hierarchy of energy scales:

(1) High energy option

$$\frac{\Delta m^2_{13}}{E} \sim a(x) \gg \frac{\Delta m^2_{12}}{E} \tag{5}$$

(2) Low energy option

$$\frac{\Delta m^2_{13}}{E} \gg a(x) \sim \frac{\Delta m^2_{12}}{E} \tag{6}$$

Now let us discuss the high and low energy options one by one. The focus will be on the sign of Δm^2_{13} in the former and the CP violation in the latter.

3.1. High energy option: matter enhanced θ_{13} mechanism

In the high energy option one can formulate perturbation theory by regarding the 1st and the 2nd terms in the Hamiltonian in (2) as unperturbed part and the 3rd term as perturbation; solar Δm^2 perturbation theory. The unperturbed system is essentially the two-flavor MSW system and it is well known that it leads to the matter enhanced θ_{13} mechanism in neutrino (if $\Delta m^2_{13} > 0$) or antineutrino (if $\Delta m^2_{13} < 0$) channels. Therefore, the high energy option is advantagious if θ_{13} is extremely small.

In leading order one can easily compute the oscillation probability in matter under the adiabatic approximation. It reads

$$P(\nu_\mu \to \nu_e) = s^2_{23} \sin^2 2\theta^M_{13} \sin^2 \left(\xi_{HE} \frac{\Delta m^2_{13} L}{4E} \right) \quad (7)$$

$$\sin 2\theta^M_{13} = \frac{\sin 2\theta_{13}}{\xi_{HE}}, \quad (8)$$

where

$$\xi_{HE} = \sqrt{(\cos 2\theta_{13} \pm \frac{2Ea}{\Delta m^2_{13}} c^2_{13})^2 + \sin^2 2\theta_{13}} \quad (9)$$

where $\pm$ refers to antineutrino and neutrino channels, respectively.

Let us expand the oscillation probability by the parameter $\frac{\Delta m^2_{13} L}{4E}$. In fact, it is a small parameter in most of the practical cases;

$$\begin{aligned} \frac{\Delta m^2_{13} L}{4E} &= 0.127 \\ &\times \left(\frac{\Delta m^2_{13}}{10^{-3} \mathrm{eV}^2} \right) \left(\frac{L}{1000\mathrm{km}} \right) \left(\frac{E}{10\mathrm{GeV}} \right)^{-1} \end{aligned} \quad (10)$$

Then, the oscillation probability reads to next to leading order as

$$\begin{aligned} P(\nu_\mu \to \nu_e) &= s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta m^2_{13} L}{4E} \right)^2 \\ &\times \left[1 - \frac{1}{3} \xi^2_{HE} \left(\frac{\Delta m^2_{13} L}{4E} \right)^2 \right] \end{aligned} \quad (11)$$

The first term in (11) is identical with the vacuum oscillation probability P_{vac} under the small $\frac{\Delta m^2_{13} L}{4E}$ approximation. It is the simplest version of the vacuum mimicking mechanism discussed in Ref. [17] where a much more extensive version including the CP (or T) violating piece is uncovered.[1]

If the measurement is done in both neutrino and antineutrino channel, one may obtain the difference

$$\begin{aligned} \Delta P &\equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e}) \\ &\simeq \frac{8}{3} \left(\frac{Ea}{\Delta m^2_{13} L} \right) \left(\frac{\Delta m^2_{13} L}{4E} \right)^2 P_{vac} \end{aligned} \quad (12)$$

If I use $\Delta m^2_{13} = 3 \times 10^{-3}$ eV^2, $\Delta P \sim 0.1 P_{vac}$ for baseline $\sim$ 1000 km and energy $\sim$ 10 GeV since the first parencesis is of order unity in the high energy option. Thus, the sign of Δm^2_{13} is determined as the sign of ΔP [20].

My next and the last message about the high energy option is that the CP violating effect is small. It is obvious in leading order that no CP violating effect is induced; it is a two-flavor problem and hence there is no room for CP violation even in matter. Therefore, we have to go beyond the leading order to have CP violation. Then, the CP and T violating effect is always accompanied by the suppression factor $\frac{\Delta m^2_{12}}{\Delta m^2_{13}} \simeq 0.1 - 0.01$ which comes from the energy denominator. Therefore, CP-odd effect is small in the high energy option.[2]

[1]In passing I have a few comments on the vacuum mimicking mechanism. It might be curious that it works at the MSW resonance point because the mixing angle is certainly exhanced. But it works in such a way that there is a prolongation of oscillation length which exactly cancels the exhacement of the mixing angle [17]. But the phenonenon of vacuum mimicking is more general which occurs not only off resonance but also in nonresonant channel as far as neutrino path length is shorter than the vacuum oscillation length. This mechanism has triggered some interests quite recently [18,19].

[2]It appears that this statement made some of the neutrino factory workers unhappy; probably they felt it difficult to reconsile this statement with the reported enomous sensitivities that extends toward a very small value of $\sin^2\theta_{13}$ which will be achieved by neutrino factory [21]. However, it appears that they are actually consistent because the sensitivity is in fact achieved by the CP conserving $\cos\delta$ term not by the CP violating term in the oscillation probability at least for $L \lesssim 1000$ km [22].

3.2. Low energy option: matter enhanced θ_{12} mechanism

The high energy option is certainly advantagious for the determination of the sign of Δm^2_{13} thanks to larger matter effects by available longer baseline due to better focusing of the ν beam. On the other hand, I will show that the low energy option is the natural place to look for genuine CP violation.

Because of the hierarchy in the energy scale (6), the first term in the Hamiltonian in (2) is the unperturbed term and the matter and the Δm^2_{12} terms are small perturbations. It is important to recognize that it is a degenerate perturbation theory because of the degeneracy in the unperturbed Hamiltonian. Then, one must first diagonalize the degenerate subspace to obtain *zeroth order* wave function and the first order correction to the energy eigenvalues. Then, the zeroth order wave function contains the CP violating phase effect. This is the reason why the low energy option allows large CP violation unsuppressed by the hierarchical mass ratio $\frac{\Delta m^2_{12}}{\Delta m^2_{13}}$, which is to my knowledge the unique case.

In this setting one can derive the oscillation probability $P(\nu_\mu \to \nu_e)$ as follows:

$$
\begin{aligned}
P\ & (\nu_\mu \to \nu_e) \\
=\ & 4 s^2_{23} c^2_{13} s^2_{13} \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right) \\
+\ & c^2_{13} \sin 2\theta^M_{12} [(c^2_{23} - s^2_{23} s^2_{13}) \sin 2\theta^M_{12} \\
+\ & 2 c_{23} s_{23} s_{13} \cos\delta \cos 2\theta^M_{12}] \sin^2\left(\xi_{LE} \frac{\Delta m^2_{12} L}{4E}\right) \\
-\ & 2 J_M(\theta^M_{12}, \delta) \sin\left(\xi_{LE} \frac{\Delta m^2_{12} L}{2E}\right) \qquad (13)
\end{aligned}
$$

where $\xi_{LE} = \xi_{HE}(\theta_{13} \to \theta_{12}, \Delta m^2_{13} \to \Delta m^2_{12})$, and J_M is the matter enhanced Jarlskog factor. The probability (13) represents, apart from the $\cos\delta$ term which is small due to the factor s_{13}, the vacuum mimicking mechanism in its most extensive form including the CP violating Jarlskog term. To check how well the system mimics vacuum oscillations see Ref [17].

The number of appearance events in water Cherenkov detector for a beam energy E = 100 MeV is estimated by assuming 10 times stronger ν_μ flux at $L = 250$ km than the K2K design flux (despite lower energy!) and 100% conversion of ν_μ to ν_e as

$$
N \simeq 6300 \left(\frac{L}{100\ \mathrm{km}}\right)^{-2} \left(\frac{V}{1\ \mathrm{Mton}}\right) \left(\frac{\mathrm{F}_{250}}{10 F_{K2K}}\right) \qquad (14)
$$

where F_{250} and F_{K2K} are the assumed flux at a detector at $L = 250$ km and the design neutrino flux at SK in K2K experiment, respectively. The latter is approximately, $3 \times 10^6 \left(\frac{\mathrm{POT}}{10^{20}}\right)$ cm^{-2} where POT stands for proton on target.

To estimate the optimal distance we compute the expected number of events in neutrino and anti-neutrino channels as well as their ratios as a function of distance by taking into account of neutrino beam energy spread. For definiteness, we assume that the average energy of neutrino beam $\langle E \rangle = 100$ MeV and beam energy spread of Gaussian type with width $\sigma_E = 10$ MeV. We present our results in Fig. 2.

While this particular proposal may have several experimental problems it is sufficiantly illuminative of the fact that the low energy option is in principle more appropriate for experimental search for CP violating effect. There is a large CP violation and the matter effect is small or controllable. The remaining question is of course how to develop a feasible experimental proposal. A possibility which employs medium energy ($\sim 1-2$ GeV) conventional ν beam is raised by an eminent experimentalist and triggered much interests [23].

There were many debates between supporters of high and low energy options in the workshop. I have concluded with my personal best three flavor scenario; we measure CP violation by low energy superbeam in Japan, and you measure δ by neutrino factory in Europe, and then let us compare the results!

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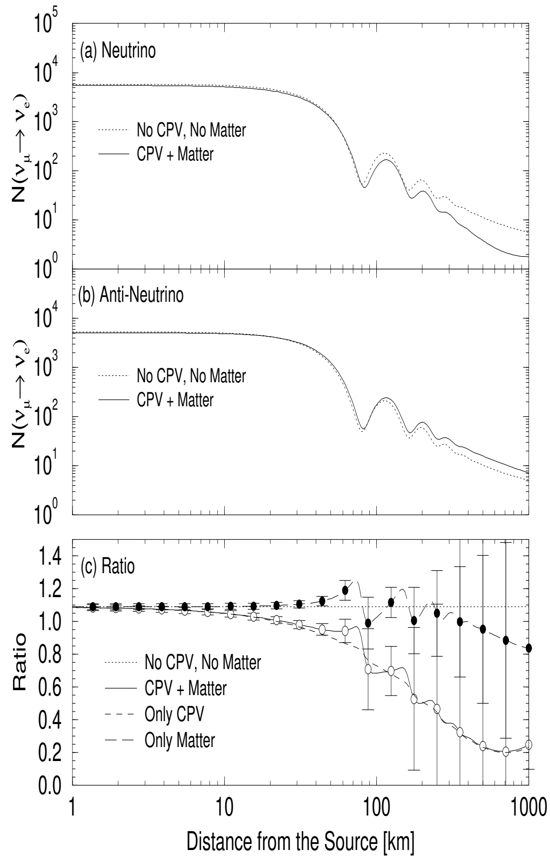

Fig.2: Expected number of events for (a) neutrinos, $N(\nu_\mu \to \nu_e)$, (b) anti-neutrinos, $N(\bar{\nu}_\mu \to \bar{\nu}_e)$, and (c) their ratio $R \equiv N(\nu_\mu \to \nu_e)/N(\bar{\nu}_\mu \to \bar{\nu}_e)$ with a Gaussian type neutrino energy beam with $\langle E_\nu \rangle =$ 100 MeV with $\sigma = 10$ MeV are plotted as a function of distance from the source. Neutrino fluxes are assumed to vary as $\sim 1/L^2$ in all the distance range we consider. $\sin^2 2\theta_{13}$ is taken as 0.1, a "maximal value" allowed by the CHOOZ limit. The remaining mixing parameters used are of the LMA MSW solution; see [17]. The error bars are only statistical.

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