

Phenomenology of future long-baseline neutrino experiments

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Abstract. I review some basic ideas behind possible future long-baseline neutrino experiments to determine the neutrino mass hierarchy and uncover leptonic CP violation. With emphasis of “large θ_{13} ” hypothesis I try to illuminate the principles of the conventional method for resolving the mass hierarchy by using the earth matter effect, and for detecting CP violation as a vacuum effect. They include the VLBL on-axis approach and the two-detector method. Some unconventional ideas for reaching the same goal are also mentioned.

1. Introduction

This is ten years from the Neutrino '98 conference in Takayama where the discovery of neutrino oscillation was announced [1]. It had a big impact on our understanding of neutrinos and has changed the field. As everybody knows, the ten years after the Takayama declaration were full of excitements in neutrino physics, the era of “sturm und drang”. The solar neutrino flavor transformation first indicated by Davis was confirmed to exist [2], and neutrino oscillation of the solar sector was discovered [3] which completely settled the solar neutrino puzzle. Now, neutrino mass and the lepton flavor mixing became a part of our “everyday life”.

Nonetheless, I would like to emphasize that we still live in a dark age; We do *not* know how large is θ_{13} , the key parameter of our understanding of the MNS matrix [4] and for further exploration of its structure including leptonic CP violation and the mass hierarchy, the mysteries still hid in a fog.

2. Coining into a large θ_{13}

An interesting question is how large is θ_{13} . In this talk, I argue that it must be large. Since the MNS matrix is the product of two matrices which diagonalize the lepton and the neutrino mass matrices, one out of three angles cannot be too small given the fact that the remaining two are large. If it turns out that θ_{13} is really small, $\sin^2 2\theta_{13} \ll 0.1 - 0.01$, there must be some reasons for it. Most probably, a symmetry is hidden behind the extremely small unique lepton mixing angle θ_{13} . An example for such possibility is the $\mu - \tau$ symmetry; For a review, see e.g., [5].

If the large θ_{13} hypothesis is correct, we have a much better hope in making progress. The reactor θ_{13} measurement [6] as well as muon neutrino superbeam experiment would detect evidence for non-zero θ_{13} . If it exists just below the Chooz bound [7] we are very close to an exciting discovery; We could have a great news of discovery of θ_{13} even before Neutrino 2010 by the soon-to-start reactor [8] and the accelerator [9] experiments. If this is the case, my talk would be the last one in this series of conference in the “medieval era” before Renaissance.

3. Focusing on CP violation and the mass hierarchy

In the rest of my talk I would like to focus in on leptonic CP violation and the neutrino mass hierarchy. I believe that they are the core subjects in contemporary neutrino research, as indicated by the fact that so many efforts were devoted to investigate how it can be measured and what would be the implications to particle physics. Regrettably, I cannot cover the topics related to the Majorana CP violation by limiting the context of my talk to long-baseline (LBL) accelerator neutrino experiments. In this talk, I concentrate on the method by which they can be searched for and discuss several conventional and unconventional ways without so much relying on the particular projects.

4. Formulating strategy for the mass hierarchy and CP

Here, I start by making an empirical observation that no project so far known has potential of resolving mass hierarchy and detect CP violation with a single detector and (nearly) monochromatic neutrino beam. This fact speaks by itself; We need to alter at least one of the conditions, or even both, to have capabilities of detecting the mass hierarchy and CP in a single project. The first option is to vary neutrino energy E , while the second is to place two (or more) detectors at different baselines.

To understand the reasons behind the empirical fact we analyze general structure of the neutrino oscillation amplitude. The S matrix which derives the appearance oscillation probability as $P(\nu_\mu \rightarrow \nu_e) = |S_{e\mu}|^2$ is given by

$$\begin{aligned}
S_{e\mu} = & s_{23} \sin 2\theta_{13} \frac{\frac{\Delta m_{31}^2 L}{4E}}{\frac{\Delta m_{31}^2 L}{4E} - \frac{aL}{2}} \sin \left(\frac{\Delta m_{31}^2 L}{4E} - \frac{aL}{2} \right) \\
& + \exp \left[i \left(\delta + \frac{\Delta m_{31}^2 L}{4E} \right) \right] \sin 2\theta_{12} c_{23} c_{13} \left(\frac{\Delta m_{21}^2 L}{4E} \right) \frac{\sin \left(\frac{aL}{2} \right)}{\left(\frac{aL}{2} \right)}, \quad (1)
\end{aligned}$$

where $a \equiv \sqrt{2}G_F N_e$. Notice that we have used the variables in the form that directly appear in the evolution equation of neutrinos. One notices that the important part of the S matrix has the structure $\frac{|\Delta m_{31}^2|L}{4E} \mp \frac{aL}{2}$ where $- (+)$ sign is for neutrino channel with normal hierarchy or antineutrino channel with inverted hierarchy (antineutrino channel with normal hierarchy or neutrino channel with inverted hierarchy). Remember that aL is energy independent but $\frac{|\Delta m_{31}^2|L}{4E}$ does depend on E . Therefore, when the spectrum analysis is carried out, the relative weight of the vacuum and the matter effects is different in each energy bin.¹ Since the mass hierarchy can be signaled by the way how the vacuum and the matter effects interfere with each other, analysis with many energy bins which span a few oscillation periods would be a powerful indicator of the mass hierarchy. This is the secret of the high resolving power possessed by the so called “on-axis wide-band beam” approach, which hereafter will be referred to as the VLBL on-axis approach. It was first formulated in a concrete way in [10] and now it is a part of the “project X” in Fermilab [11]. Its high resolving power should not come as a surprise because the energy resolved oscillation data which span 2-3 periods of oscillation, assuming perfect event reconstruction, must contain “everything of the neutrino oscillation”.

The next question I want to address is how CP violation can be signaled. By nature CP violation is the vacuum effect. The matter effect does not quite enhance it, but mostly acts as a background. Therefore, measurement at relatively short baseline of $\lesssim 1000$ km, in principle, can do a better job, the strategy of low energy ν_μ superbeam [12]. To look more closely what is

¹ Notice that this feature is not shared by varying L approach because both of the terms scale uniformly.

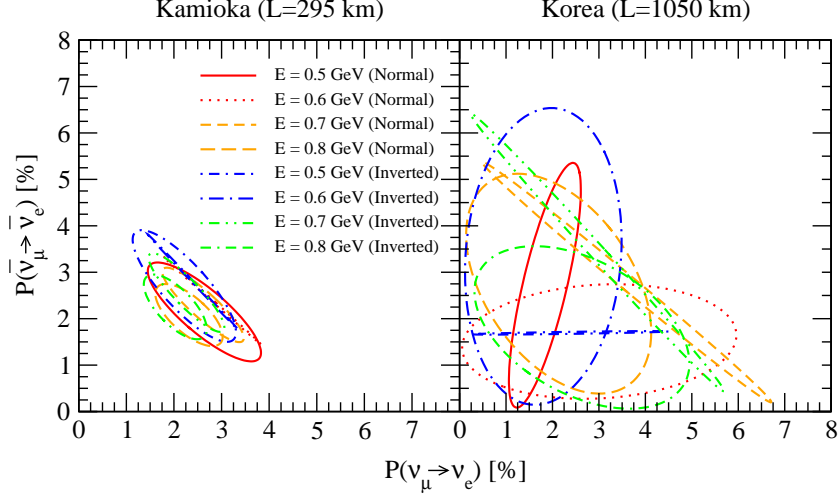


Figure 1. Energy dependences of the oscillation probabilities for $\sin^2 2\theta_{13} = 0.05$ are represented by plotting ellipses (which results as δ is varied from 0 to 2π) in bi-probability space [13] for various neutrino energies from 0.5 to 0.8 GeV. The left and the right panels are for detectors in Kamioka and in Korea, respectively. The ellipses in upper 4 symbols (warm colors) indicate the ones of normal mass hierarchy ($\Delta m_{31}^2 > 0$) and the one of lower 4 symbols (cold colors) the ones of inverted mass hierarchy ($\Delta m_{31}^2 < 0$). The figure is taken from [14].

the key in this approach I write down the atmospheric-solar interference term in $|S_{e\mu}|^2$,

$$\begin{aligned}
 |S_{e\mu}|_{(\text{interference})}^2 &= 8J_r \left(\frac{\Delta m_{21}^2 L}{4E} \right) \left(\frac{\frac{\Delta m_{31}^2 L}{4E}}{\frac{\Delta m_{31}^2 L}{4E} - \frac{aL}{2}} \right) \cos \left(\delta + \frac{\Delta m_{31}^2 L}{4E} \right) \\
 &\times \left[\sin \left(\frac{\Delta m_{31}^2 L}{4E} \right) - \cos \left(\frac{\Delta m_{31}^2 L}{4E} \right) \sin \left(\frac{aL}{2} \right) \right] + \mathcal{O}((aL)^2). \quad (2)
 \end{aligned}$$

Notice that the matter effect is relatively small at $L = 1000$ km, $\frac{aL}{2} = 0.27 \left(\frac{\rho}{2.8\text{g/cm}^3} \right) \left(\frac{L}{1000\text{km}} \right)$. When the baseline L is changed, the trigonometric nature of the terms in (2) manifests itself, allowing sensitive detection of CP violation. See Fig. 1. If the spectrum information is also provided, the sensitivity to CP violation would be amplified, which appears to be the case in the Tokai-to-Kamioka-Korea (T2KK) setting [14, 15]. It should be remarked, however, that the original T2K II setting with a megaton HK only at Kamioka seems to have a comparably good sensitivity to CP [14]. With spectrum informations, the method of low energy superbeam for CP violation is working extremely well, may be much better than originally expected.

5. From principle to practicality

From experimental point of view, it is important to discuss how the principles for determining the mass hierarchy and detection of CP violation discussed above can be implemented into the realistic experimental setup. This issue is particularly important for the on-axis VLBL setup. Since the neutrino beam has high energy component of ~ 10 GeV, NC and CC reactions on nucleons produces background events which accumulate in low energy region. It appears that it is highly nontrivial to disentangle them from the genuine ν_e appearance events in water Cherenkov detectors. See e.g., Figs. 5 and 9 in [16]. It is worth to note in this and the other contexts that an extensive effort is currently devoted to examine and to improve the performance of liquid Ar

detectors [17]. In particular, once the liquid Ar detector with ~ 100 kton size becomes feasible, it would greatly enhance the physics potential of conventional superbeam experiments. See e.g., [18].

On the other hand, if you rely on the two-detector method with almost equal off-axis angle, such as “two identical detector” approach [14, 15],² the problem of background rejection (most of them are π^0) is less severe even in water. It is partly because this problem has been examined to a great detail in the context of the next generation accelerator experiments [9, 19], but also because of cancellation of systematic errors between the two detectors, as explicitly demonstrated in [14].

An important key word for discovery of leptonic CP violation is the robustness. The evidence for CP violation must be demonstrated in such a way that underestimation of the systematic errors, for any unknown reasons, cannot alter the conclusion. In this respect, the cancellation of the errors in the two-detector setting is advantageous, as is the case in the reactor θ_{13} experiments [6], and its robustness for CP violation discovery is made explicit in [20]. The result has to be stable against matter density variation with conservative estimation of the uncertainties in local chemical composition along the neutrino trajectory in the earth, which can be large. I believe that these caution has to be kept in mind because most of the currently known experimental setups to look for genuine CP violation require separation from the background matter effect; We lack a clean “ $K_L \rightarrow 2\pi$ ” signal in searching for leptonic CP violation. In this context, one of the most important points, which cannot be over-emphasized, is to accumulate reliable and accurate neutrino cross section data [21].

6. Unconventional ideas; An advanced course

Though LBL experiments with use of appearance channel are likely to provide the most promising way for determining the mass hierarchy and CP, there have been proposed several unconventional ways to do the job. Let me mention some of them. I start from the “disappearance method”.

- It is usually granted that the effects of CP violation is small in the disappearance channels. However, it is proposed that ν_μ disappearance measurement at very long baseline such as $L \sim 5000$ km and at low energies $E \sim 400$ MeV can be sensitive to CP violation [22].
- If the Mössbauer neutrinos [23] are available, the monochromatic $\bar{\nu}_e$ beam can be used as a mean for precision measurement of $\Delta m_{31}^2(ee)$ with accuracy of sub% level [24]. If the accuracy in measuring $\Delta m_{31}^2(\mu\mu)$ in ν_μ disappearance channel can be made comparable³ it would give us chance of determining the hierarchy by the sign of $\Delta m_{31}^2(ee) - \Delta m_{31}^2(\mu\mu)$ [25], a realization of the method proposed in [26].
- The Mössbauer neutrinos can also serve as a mean for *in situ* determination of not only the mass hierarchy but also the solar parameters. The secret for sensitivity to the mass hierarchy is that it may resolve the “interference” between Δm_{32}^2 and Δm_{31}^2 oscillations, and identify which has an advanced phase [27]. (This is our interpretation for the method proposed in [28].)

Notice that though people usually assume that the matter effect is indispensable to resolve the mass hierarchy, it is not quite true. In the latter two methods above only the vacuum effect

² My prejudice is that the two-detector setting with spectrum informations is effectively close to the wide-band beam approach, but retaining only a relatively clean part by cutting off the background rich “dirty part”.

³ It must be remarked [25], however, that the accuracy of $\Delta m_{31}^2(\mu\mu)$ determination is limited by uncertainty in calibration of absolute energy scale, which is believed to be hard to go down from the current estimation of $\simeq 2\%$ in Super-Kamiokande. This problem is crucially important for any apparatuses which aim at measuring Δm_{31}^2 to a sub% level.

is sufficient. Let me mention another example in this context: CERN-MEMPHYS setting [29] is known as a “near vacuum” experiment. Yet, the analysis done in [30] indicates that it has sensitivity to the mass hierarchy to $\sin^2 2\theta_{13} \simeq 0.03$ before combining with atmospheric neutrino data. Though the result is somewhat counter intuitive, the major part of the sensitivity appears to come mainly from the CPT conjugate channels, as interpreted by the authors of [31] who adopt just that combination to solve the mass hierarchy.

7. If θ_{13} is small, or if it is large

If θ_{13} is really small, $\sin^2 2\theta_{13} \ll 0.01$, we need something else. The most popular idea is either neutrino factory [32] or the beta beam [33]. While I do not go into detail, the physics potential of the advanced apparatuses for θ_{13} and CP is known to be extremely good [34]. It also gives us an opportunity to look for non-standard neutrino interactions with matter to a strength $10^{-4} - 10^{-3}$ times weaker than weak interactions in a way that does not disturb precision measurement of the standard mixing parameters [35].

Here, a question can be raised: If θ_{13} is large as I argued before, how these machines which are motivated for exploring small θ_{13} region survive, or adjust themselves to the new situation? An answer is provided; Low energy neutrino factory [36, 37]. The idea is to use relatively low muon energy $E \simeq 5$ GeV and a “short” baseline of $\simeq 1500$ km. The potential of resolving the θ_{23} octant degeneracy (which is known to be a tough problem, see e.g. [15]) by using only the ν_μ disappearance channel, as illustrated in [36], indicates that an extremely clean environment is realized in the setting. As a consequence, the sensitivities to the mass hierarchy and CP are also shown to be excellent.

8. Conclusion

I tried to cover the orthodox as well as unconventional ideas for determining the neutrino mass hierarchy and pinning down CP violation. If you go through a survey of the various future LBL projects for the mass hierarchy and CP, despite mine is a very incomplete one, you must feel that they are all quite reasonable. Important thing is *not* to argue which is (slightly!) better than the others, but to make at least one of them happen. I hope that people renew recognition of this point and the fact that it will give our whole community momentum to realize the inevitably big projects in the near future. My personal prejudice is that θ_{13} is relatively large. If it is true it further encourages us to proceed to search for lepton CP violation and determination of the mass hierarchy. Let us wait and see what happens toward Neutrino 2010 in Athens!

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