

If θ_{13} is large, then what?

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Abstract. As indicated by the recent data obtained by the T2K and the MINOS experiments θ_{13} can be large, even be comparable to the Chooz limit. Assuming that it will be confirmed by ongoing reactor and accelerator experiments I discuss its possible implications in the context of how to explore the remaining unknowns in the lepton flavor mixing. While it opens wide range of possibilities to explore CP and the mass hierarchy, I emphasize that the large θ_{13} allows us to take “all in one” (everything in a lunch box) approach.

1. It was a speculative title when it was proposed

You might have suspected that my title is too timely, but as a matter of fact, it was a speculative one when it was proposed to one of the conveners in early May, much earlier than the announcement of ν_e appearance events at T2K [1]. The resulted six clean events which fulfill the criteria for electron-like events in SK strongly suggest that θ_{13} has a nonzero value. Their best fit value is around $\theta_{13} \sim 10^\circ$ close to the Chooz limit [2]. It was soon followed by the MINOS collaboration which also obtained a relatively large value of θ_{13} [3]. In fact, by taking account of these new data from T2K and MINOS into the global analysis the Bari group concluded that it implies evidence for nonzero θ_{13} at confidence level (CL) higher than 3σ [4]. The best fit value is $\theta_{13} \simeq 8^\circ$. See also [5]. I believe it an urgent matter to discuss what are the consequences of suggested large values of θ_{13} though it must be confirmed by the further running of these experiments as well as the ongoing reactor θ_{13} experiments [6, 7, 8].

2. Why θ_{13} so large?

I stated in a talk in Neutrino 2008 in Christchurch that “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” [9]. Here is a brief recapitulation of the very simple reasoning which led me to the above statement. The lepton flavor mixing matrix, the MNS matrix [10], U_{MNS} , is a “relative matrix” $U_\ell^\dagger U_\nu$, where U_ℓ and U_ν denote the unitary matrices which diagonalize the charged lepton and the neutrino mass matrices, respectively. The MNS matrix is composed of the three angles θ_{ij} ($i, j = 1 - 3$) and a CP violating phase δ_ℓ , the lepton analogue of the quark Kobayashi-Maskawa phase δ_q [11]. Two of the angles are known to be large, $\theta_{12} \simeq 34^\circ$ and $\theta_{23} \simeq 45^\circ$. Then, it is highly unlikely that only the remaining angle θ_{13} is extremely small, unless there is a good reason for tuning only θ_{13} into a small value. That is, if a symmetry exists such that θ_{13} vanishes at the symmetry limit, there is a natural reason why only θ_{13} is small among the three mixing angles. There exists many examples for such symmetry including $\mu - \tau$ symmetry and discrete symmetries. For a review see [12]. It is my prejudice

that the large θ_{13} suggested by T2K and MINOS measurement, if confirmed, would give a tough time for these symmetries which aims at explaining small θ_{13} , unless a large correction to the symmetry limit is shown to be naturally induced.

3. Wide range of possibilities are now open for measuring CP and mass hierarchy

Without having compelling reasons for large θ_{13} , one had to take into account the possibility that θ_{13} is small in thinking about ways for measurement of CP phase and determination of the neutrino mass hierarchy. That is why many of the existing proposals for such apparatus naturally include those that have sensitivities to a tiny value of θ_{13} with varying limiting values. They include, for example (sorry for my arbitrary choice), neutrino factory [13, 14], beta beam [15], superbeam enriched with two detectors [16], and their combination [17]. For their sensitivities see [18]. I wonder, however, that racing for θ_{13} sensitivity could have produced an atmosphere that the better facility is the one which has sensitivities to smaller values of θ_{13} . In seeing the T2K and MINOS indication for large θ_{13} , I believe that it is the time to start thinking about changing the gear to more relevant things.

What is good if θ_{13} is as large as $\sim 10^\circ$? My first answer is that a wide range of possibilities becomes open for strategies and setups aiming at exploring lepton CP violation through neutrino oscillation. I believe that in the context of conventional superbeam [19] unambiguous evidence for lepton CP violation requires a megaton scale water Cherenkov detector, or a ~ 100 kton liquid Ar detector [20, 21, 22]. Yet, the suggested large value of θ_{13} , still need to be confirmed and assumed here, stimulates to examine other possibilities such as reactor-accelerator combined method [23], combining different accelerator measurement [24, 25, 26], or the one adding one more new facility which may or may not require an extensive cost [17, 27]. Some more exotic options are discussed in [9]. It is notable that the CERN-MEMPHYS project, despite an almost vacuum setting, has a reasonable sensitivity to the mass hierarchy to $\sin^2 2\theta_{13} \simeq 0.03$ before combining with atmospheric neutrino data [28].

Sometime ago the CP sensitivity achievable by the reactor-accelerator combined method was examined in detail [29]. The results obtained in this analysis indicate that combining data taken and to be taken by all planned experiments is not enough to guarantee discovery of CP violation in δ_ℓ coverage of more than 30% in most of the allowed region of θ_{13} even though one assumes that the mass hierarchy is known. It should be noticed, as observed and emphasized in [23], that the CP sensitivity is severely damaged by the parameter degeneracy due to unknown neutrino mass hierarchies [30]. For a recent overview of the parameter degeneracy see [31].

4. “All in one” approach becomes feasible

I believe that the one of the most important implications of the assumed large value of θ_{13} is that one can think of “all in one” (*obento* in Japanese, everything in a lunch box) approach. As we saw in the above, a traditional approaches for CP and the mass hierarchy entailed in aggressive proposals [13, 15, 16, 17] to include a very small value of θ_{13} within the scope. Though powerful and the redundancy is of course welcome, they may not be the optimal cost-effective apparatus for large θ_{13} . To my opinion, what is good in living in the world with large θ_{13} is that one can achieve the same goal by less expensive “all in one” setting. More concretely, I mean by it a single detector (such as a megaton water Cherenkov detector) assuming prior existence of intense neutrino beam. Timely enough the LOI of Hyper-Kamiokande (Hyper-K) project has just appeared [32]. Therefore, let us briefly discuss the spirit of the “all in one” approach by taking this concrete setting.

With intense neutrino beam from 1.66 MW proton driver at J-PARC it is demonstrated that Hyper-K with 0.56 megaton fiducial mass has a superb performance for discovery of CP violation, which covers most of the region of θ_{13} allowed at 3σ CL [4]. See Fig. 24 of [32] which assumes the known mass hierarchy and for 1.5 (3.5) years of neutrino (antineutrino) running.

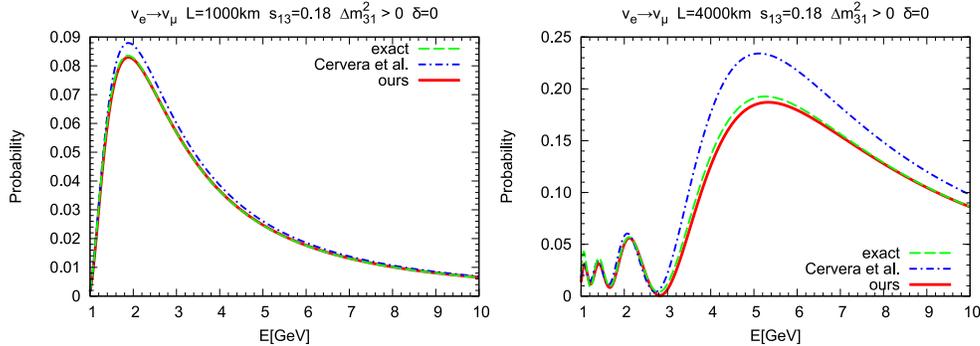


Figure 1. Comparison between the exact oscillation probability $P(\nu_e \rightarrow \nu_\mu)$ computed numerically as a function of energy (---), calculated by using the second-order formula in [14] (— · —), and with our formula with large θ_{13} corrections (—). The left and right panels are for baselines $L = 1000$ km and $L = 4000$ km for which the matter density is taken as 2.8 g/cm³ and 3.6 g/cm³, respectively.

It shows a remarkable accuracy of determination of δ_ℓ with 1σ error smaller than 20 degree for $\sin^2 2\theta_{13} \gtrsim 0.03$. However, if the mass hierarchy is unknown the analysis suffers from the sign- Δm^2 degeneracy [30].

While allowing clean measurement of CP violation, a drawback of setting with such short baseline is that it is difficult to determine the mass hierarchy, another important goal of future neutrino experiments. That is why many proposals for determining all the unknowns in neutrino parameters exploit baselines of several thousand km. If θ_{13} is large, however, the mass hierarchy can be determined by high-statistics observation of atmospheric neutrinos, the idea discussed by many authors. See [33, 34] for early references. The analysis presented in [32] indicates that the sensitivity to the mass hierarchy depend very much on which octant θ_{23} lives but it can be carried out by $\sim 3 - 10$ years running of Hyper-K for large θ_{13} . It should also be mentioned that having other capabilities such as proton decay discovery is of crucial importance. I emphasize that the realization of “all in one” approach is, of course, not limited to this particular version discussed above. But, it is certainly encouraging to see the concrete example appeared which is armed with the realistic simulations based on their long-term experiences at Super-K.

5. Large- θ_{13} perturbation theory of neutrino oscillation

Is theoretical treatment of neutrino oscillation well oiled when a large value of θ_{13} close to the Chooz limit is established? For example, does the well known treatment of the degeneracy [31] need modification? If yes, to what extent?

To answer these questions a framework dubbed as “ $\sqrt{\epsilon}$ perturbation theory” ($\epsilon \equiv \Delta m_{21}^2 / \Delta m_{31}^2$) has been formulated [35] by assuming $s_{13} \sim \sqrt{\epsilon} \simeq 0.18$, which roughly corresponds to the Chooz limit. By doing so one can systematically compute the large- θ_{13} corrections to the formula in [14]. While large corrections arise in certain limited region of energy and baseline as indicated in Fig. 1, one can show on general ground that the correction terms are of order $\sim \epsilon^2 \simeq 10^{-3}$. By general argument one can show that they are the terms proportional to either s_{13}^4 or ϵs_{13}^2 [35]. Therefore, the large- θ_{13} correction to the degenerate solutions obtained with the formula in [14], generally speaking, is not sizable. See [35] for more detail.

6. Conclusion

Assuming that the T2K and MINOS hints for large θ_{13} will be confirmed, I argued that we are at the turning point of thinking of our strategy of how to explore the remaining unknowns in

the lepton flavor mixing. In particular, it allows us to rely on “all in one” approach. I hope that the personal view can be strengthened by further exploration toward Nufact 2012.

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