Resolving the octant $\theta_{23}$ degeneracy by neutrino oscillation experiments

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We discuss how and to what extent the degeneracy associated with $\theta_{23}$, if it’s not maximal, can be resolved by future oscillation experiments which utilize conventional neutrino beam from accelerator and/or reactor neutrinos.

1. Introduction

Physics of neutrinos will soon be entering into the era of precision physics. Proposed projects such as T2K [3] and NOνA [4] experiment will be able to measure the mixing parameters responsible for atmospheric neutrino oscillation, $\sin^2 2\theta_{23}$ and $\Delta m^2_{23}$ with a few percent uncertainty. Moreover, these experiments can probe $\sin^2 2\theta_{13}$ down to $\sim 10^{-2}$ or smaller. If non-zero $\theta_{13}$ will be established, the future phases of these experiments will be aimed to determine the CP violating phase as well as the mass hierarchy [3,4] (see also [5]).

It has been known that in order to perform precise determinations of neutrino mixing parameters including the CP phase and mass hierarchy, one must confront with the problem of so called parameter degeneracy. There are 3 types of such degeneracy, octant [6], intrinsic [7] and sign $\Delta m^2$ [8] degeneracy. Here we focus only on the octant degeneracy, which is decoupled from the other ones with a good approximation in our experimental set up. We consider only experiments based on the conventional neutrino beam from accelerator and reactor neutrinos.

Suppose that $\theta_{23}$ is different from $\pi/4$. Disappearance $\nu_\mu \rightarrow \nu_\mu$ experiment can determine quite precisely the value of $\sin^2 2\theta_{23}$ with 1% uncertainty [3] but this does not allow us to know in which octant $\theta_{23}$ lives, and leads, at first approximation, ignoring $\theta_{13}$, to the following 2 degenerate solutions, $\sin^2 \theta_{23} = \frac{1 \pm \sqrt{1 - \sin^2 2\theta_{23}}}{2}$. For example, $\sin^2 \theta_{23} = 0.4$ or 0.6 (0.45 or 0.55) if $\sin^2 2\theta_{23} = 0.96$ (0.99). How and to what extent this can be resolved is the topics of this talk.

2. Combining Accelerator and Reactor

Let us first discuss the possibility to resolve this degeneracy by combining accelerator and reactor neutrinos [1], based on the suggestion in [10]. As a concrete example, we consider the second phase of the T2K experiment [3] with upgraded beam power of 4 MW and Hyper-Kamiokande (HK) detector, and high statistics second generation reactor experiment, e.g. Angra project [9]. We fix the mixing parameters relevant for solar neutrinos as $\Delta m^2_{21} = 8.0 \times 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.31$, and the atmospheric $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV$^2$. The exposures for accelerator are assumed to be 2 (6) years of neutrino (anti-neutrino) running with HK whose fiducial volume is 0.54 Mt, whereas for the reactor we assume an exposure of 10 GW-kt-yr, which is defined as a product of reactor power, detector volume and running time.

In Fig. 1 we show the process of how the octant degeneracy can be resolved by combining the results from accelerator and reactor. Figs. 1(a) and (b) show that by combining the $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$ modes from accelerator, we can get 2 separated allowed regions where one of them corresponds to the fake solution. Then if we add the result of the measurement of $\theta_{13}$ form reactor experiment, which is shown in Fig. 1(c), we can eliminate the fake solution and end up with the true one as shown in Fig. 1(d).
We show in Fig. 2 the parameter region of $\sin^2 2\theta_{13}$ and $\sin^2 2\theta_{23}$ where the octant degeneracy can be resolved. The degeneracy can be resolved for $\sin^2 2\theta_{23} \lesssim 0.96$ at 2 $\sigma$ CL for $\sin^2 2\theta_{13} \gtrsim 0.05$ (see upper panel). We confirmed the strong dependence of sensitivity on $\theta_{13}$ expected in [10].

3. Accelerator based 2 detector method

Next we discuss another possibility based on [11]. In the second phase of T2K experiment (HK with 4 MW beam), in order to improve the sensitivity to the mass hierarchy determination, it was suggested to place the second identical detector at Korea with baseline of 1050 km, in addition to the one at Kamioka. Here we assume 2 detectors are not only identical but also receive the neutrino beam with the same energy spectrum by choosing the same off axis angle (2.5 degree in this case). It was shown that this experimental set up can also resolve the octant degeneracy [2].
Figure 3. Expected number of electron (upper panels) and muon (lower panels) events as a function of the reconstructed neutrino energy for $\sin^2 2\theta_{23} = 0.40$ (open circles) and $0.60$ (filled circles). Taken from [2].

Figure 4. Region of parameters where $\theta_{23}$ degeneracy can be resolved. Light gray (dark gray) area corresponds to 2 (3) $\sigma$ significance. 0.27 Mton detectors both in Kamioka and Korea and 4 years running with neutrino beam and another 4 years with anti-neutrino beam are assumed. In left (right) 2 panels, the sensitivity is defined so that the experiment can resolve the octant degeneracy for any (half) values of the CP phase $\delta$. Taken from [2].

previous case shown in Fig. 2 where the sensitivity is significantly worse (better) when $\theta_{13}$ is small (large). We conclude that in this method, the octant degeneracy can be resolved for $\sin^2 2\theta_{23} \lesssim 0.97$ at 2 $\sigma$ CL even for very small values of $\theta_{13}$.

4. Summary

The expected sensitivities by the 2 methods we discussed show very different dependence on $\theta_{13}$. If $\theta_{13}$ is larger, close to the present limit, the method of combining accelerator and reactor would give better sensitivity whereas for smaller $\theta_{13}$, the accelerator based 2 detector methods would be better, and therefore, these 2 methods are complementary to each other. See Refs. [12] for details.

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