Prospects of precision neutrino oscillation studies with Hanohano

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1 Introduction

The recent experimental observation of neutrino oscillations has been a great success of particle physics. Experiments such as SNO [1] and KamLAND [2], managed to not only provide the evidence for the phenomenon but also measure two of the oscillation parameters, namely $\Delta m_{12}^2$ and $\theta_{12}$ with remarkable precision. However other parameters remain unknown or known with a relatively poor precision. These include $\Delta m_{13}^2$, $\Delta m_{23}^2$ and $\theta_{13}$ which are, in principle, measurable with a big KamLAND-like reactor $\bar{\nu}_e$ experiment, provided the detector size and the baselines are chosen adequately. Moreover, the measurement of $\Delta m_{13}^2$ and $\Delta m_{23}^2$ with sufficient precision will determine the neutrino mass hierarchy.

That said, the currently operating detectors are not suitable for most of those studies because of being too small or inappropriately placed or both. The measurement of $\theta_{13}$, $\Delta m_{13}^2$ and $\Delta m_{23}^2$ requires a detector with a baseline finely tuned for respective studies.

Such an ocean-based detector named “Hanohano” has been suggested [3, 4]. Its ocean-based location provides more flexibility in the choice of the baseline. Since the optimal baseline for some of the studies is fairly long, the detector has to be quite big in order not to be statistically limited. Besides the measurement of $\theta_{13}$, $\Delta m_{13}^2$, $\Delta m_{23}^2$ and, possibly, neutrino mass hierarchy, the new experiment will be able to improve the estimation of the “solar” parameters, $\Delta m_{12}^2$ and $\theta_{13}$, compared with what we know from the current experiments. The concept of a medium-baselined reactor $\bar{\nu}_e$ experiment for such studies has been thoroughly developed in [5].

Once the oscillation study is completed, the detector can be moved to a remote location in the ocean for the dedicated terrestrial neutrino study. Moreover, like any large scintillator detector, Hanohano can be used for a number of other experiments, including but not amounting to nucleon decay studies, solar neutrino observation and supernova monitoring.

The numerical analysis of the prospects of Hanohano and the requirements it must meet are presented below.
2 Oscillation study through precision spectrum measurement

In the vacuum oscillation approximation, we have the following $\bar{\nu}_e$ survival probability:

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2 \Delta_{12} + \sin^2(2\theta_{13}) \cos^2(\theta_{12}) \sin^2 \Delta_{13} + \sin^2(2\theta_{13}) \sin^2(\theta_{12}) \sin^2 \Delta_{23},
\]

For the experiment to be sensitive to $\Delta m_{13}^2$ and $\Delta m_{23}^2$, the mixing angle $\theta_{13}$ must not be zero. If it turns out to be zero or finite but extremely small, the determination of those squared mass differences through reactor $\bar{\nu}_e$ disappearance measurement becomes impossible. However a much tighter limit for the angle itself than the currently known $\theta_{13} < 0.015$ [6] will be set anyway.

This sensitivity analysis was based on the unbinned likelihood approach, where the test statistic was chosen to be the negative logarithm of the likelihood difference, which, if multiplied by two, can be proved to have a $\chi^2$ distribution for a rather general case. Although the sensitivity estimation can be carried out by the integration of spectrum dissimilarities and does not require the actual experiment simulation, the simulation has been carried out for the purpose of a cross check and was found in a perfect agreement with the “theoretical” prediction.

Only two kinds of systematic uncertainties were considered here: the general detection efficiency error, and the uncertainty in the detector energy resolution.

3 Results

The sensitivity profile for the “solar” oscillation parameters is shown in Figure 1a. The optimum baseline for the $\Delta m_{12}^2$ measurement is about 30 km, for $\theta_{12} \sim 40$ km. Provided the background is kept small and the systematic uncertainties are not extremely large, the 10-kiloton KamLAND-like detector located at 40 km from a 5 GW power plant can measure $\sin^2 \theta_{12}$ to the accuracy down to 0.005 and $\Delta m_{12}^2$ down to $0.05 \times 10^{-5} eV^2$, which is about four times better than currently known from the combined KamLAND and SNO parameter fit.

For $\theta_{13}$, the shorter baselines seem to be better, based on just statistics alone. However a bigger detector with a longer baseline was found to be much less dependent on the systematic error of the detection efficiency. At 40 km, it will be able to measure $\sin^2 2\theta_{13}$ down to 0.02, in about 2 years, which is quite competitive with the dedicated experiments currently in construction. Still longer baselines may lack in statistics and have an additional disadvantage of having dependence on the detector energy resolution estimation error.

The “atmospheric” $\Delta m_{13}^2$ and $\Delta m_{23}^2$ determination depends on the actual value of $\theta_{13}$. If $\sin^2 2\theta_{13}$ turns out to be no less than 0.05, these squared mass
differences can be determined with the accuracy of about $2.5 \times 10^{-5}\text{eV}^2$, which is about 10 times better than currently known from the baselines of up to 40-50 km. This study depends on a good detector resolution.

The hierarchy study is the most challenging one. The sensitivity for baselines shorter than the optimum 50 km deteriorates dramatically (Fig 1b). This study depends on the detector resolution much more than that for the “atmospheric” squared mass difference. Having at worst $0.025\sqrt{E_{\text{vis}}}[\text{MeV}]$ seems to be absolutely necessary since compromising it to $0.035\sqrt{E_{\text{vis}}}[\text{MeV}]$ (which would still be excellent by contemporary standards) is enough to require a four-fold increase in livetime to achieve the same accuracy. Even with the best possible resolution, this study relies on a substantially high $\theta_{13}$.

![Figure 1: Hanohano livetime necessary to measure $\sin^2 2\theta_{12}$ (solid) to 0.005 and $\Delta m^2_{12}$ (dashed) to $0.05 \times 10^{-5}\text{eV}^2$ (a); Hanohano livetime necessary to discriminate neutrino mass hierarchies to 1σ CL if $\sin^2 2\theta_{13} = 0.05$ (solid) and $\sin^2 2\theta_{13} = 0.025$ (dashed), detector energy resolution being $0.025\sqrt{E_{\text{vis}}}[\text{MeV}]$ in both cases (b).](image)

4 Conclusion

Hanohano will provide a dramatic improvement in the evaluation of almost all oscillation parameters measurable through $\bar{\nu}_e$. The optimum baseline for such an ocean-based detector is found to be 40 to 50 km but may need further adjustments, once the parameters of the detector itself are measured. The neutrino mass hierarchy study requires certain design choices for such a detector. First of all, it must be big enough. Second, it must have an outstanding energy resolution. Even if the reliable hierarchy turns out to be difficult because $\theta_{13}$ proves to be very small, the limits on all other parameters will be improved.

In addition to the oscillation measurement, the Hanohano detector will be useful for many other experiments, including nucleon decay and supernova monitoring and will provide absolutely unique opportunities for terrestrial neutrino studies.
References

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