Neutrino and Anti-Neutrino Cross Sections and CP Phase Measurement

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Intense neutrino beam and large detector such as second phase of JHF neutrino beam and Hyper-Kamiokande will enable us to measure CP phase of lepton term. The treatment of fake asymmetry in CP measurement due to cross section difference of neutrino and anti neutrino is reported. Expected CP phase measurement sensitivity and required improvement of experiments are reported as well.

1. Introduction

After the discovery of the CP violation in the quark sector, it is natural question that whether CP is also violated or not in the Lepton sector. If we find finite θ_{13}, in addition to θ_{23} and θ_{12}, the channel of measurement of CP phase in lepton sector will open and it become one of the most interesting subjects in the flavor physics.

The oscillation probability between ν_μ and ν_e is shown in the equation 1. CP phase δ and matter effect term a take opposite sign for $\bar{\nu_\mu}$ to $\bar{\nu_e}$ oscillation. In the case that CP phase δ is a finite value, third term of the equation 1 take different sign between neutrino case and anti-neutrino case. To see the asymmetry of this term, we define CP asymmetry parameter A_{CP} as:

$$A_{CP} \equiv \frac{P-\bar{P}}{P+\bar{P}} \sim \frac{\Delta m^2_{12} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin\delta \qquad (2)$$

where $P(\bar{P})$ is a oscillation probability of ν_μ to ν_e ($\bar{\nu_\mu}$ to $\bar{\nu_e}$).

The asymmetry parameter A_{CP} strongly depend not only on δ but also on other oscillation parameters that some of them have not yet been known. To discuss future CP phase measurement here, a scenario on neutrino world around year 2010 is assumed as follows.

· $\nu_\mu \to \nu_\tau$ oscillation is established by atmospheric neutrino and long baseline neutrino experiments. $\sin^2 2\theta = 1.0$ and $\Delta m^2_{23} = 3 \times 10^{-3} eV^2$.

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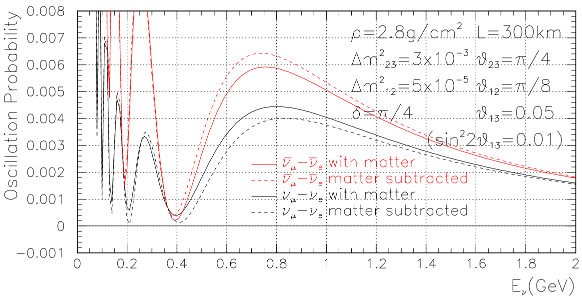

Figure 1. Oscillation probabilities for $\nu_\mu \to \nu_e$(black) and $\bar{\nu}_\mu \to \bar{\nu}_e$(red). The solid curves includes asymmetry due to matter effect. For the dashed curves, the matter effect is subtracted and the difference between $\nu_\mu \to \nu_e$(black) and $\bar{\nu}_\mu \to \bar{\nu}_e$(red) are all due to CP effect.

· Solar neutrino LMA solution is established by solar neutrino and reactor neutrino experiments. $\sin^2 2\theta_{12} = 0.8$ and $\Delta m^2_{12} = 5 \times 10^{-5} eV^2$.

· Finite θ_{13} is found by JHF-Kamioka first phase. $0.01 < \sin^2 2\theta_{13} < 0.1$.

· LSND result is excluded by Mini-Boone so that sterile neutrino does not contribute in the oscillations of active neutrinos.

· Then, still unknown parameters of neutrino oscillation are only δ and sign of Δm^2 (and absolute mass).

2. JHF-Kamioka neutrino experiments

The JHF 50GeV proton accelerator is approved and started its construction. Details of experiments which use neutrino beam from the accelerator (JHF-Kamioka neutrino experiment) are described in elsewhere [1]. The first phase experiment mainly aims precision measurement of θ_{23} and Δm^2, discovery of finite θ_{13} value. Second phase of JHF-Kamioka neutrino experiment is also planned with $\sim$4MW of accelerator power and $\sim$1Megaton water cherenkov detector. The CP phase measurement on lepton sector is a main physics topic in the second phase.

Neutrino beam will be created by an off axis beam technique that beam line itself is essentially same as conventional wide band neutrino beam with horn magnet but detectors are located intentionally a few degree off from beam axis to get a quasi-monochromatic and high intensity neutrino beam. Sign of neutrino is selected by changing polarization of horn magnet. Expected spectra of neutrino and anti-neutrino interactions observed in far detector is shown in Figure 2.

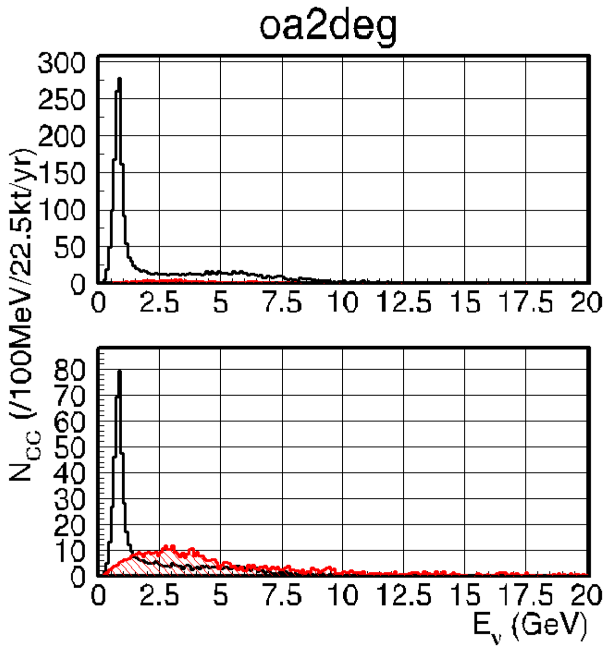

Figure 2. Energy spectrum of expected to interact in the 22.5kton water cherenkov detector, 2 degree off axis neutrino beam with 10^{21} protons on target exposure. Upper figure is neutrino beam, lower figure is anti neutrino beam. hatched histograms are interactions of wrong sign neutrino components.

3. CP phase measurement

CP phase measurement will be performed by comparing the oscillation probabilities of $\nu_\mu \to \nu_e$ in neutrino beam and $\bar{\nu_\mu} \to \bar{\nu_e}$ in anti-neutrino beam. To get same number of oscillation signal $\nu_e(\bar{\nu_e})$ interactions, anti neutrino beam needs longer beam time. We assume one year (5×10^{21} p.o.t.) for neutrino beam run and 3.66year (1.83×10^{22}p.o.t.) for anti neutrino beam run.

In the case of conventional neutrino (anti neutrino) beam, since the beam is essentially pure ν_μ ($\bar{\nu_\mu}$), oscillation probability can be measured by counting appeared ν_e ($\bar{\nu_e}$) interactions. In this measurement, most major background source is an electromagnetic shower from N.C. π^0 production. To reject this background effectively, we will use tight π^0 - electron separation in addition to an "official" ν_e selection which used in the Super-Kamiokande atmospheric neutrino analysis [2][3]. Table 1 shows expected numbers of oscillation signals and backgrounds.

The strategy for the CP measurement is as follows. To compare oscillation probabilities, we want to know

$$P_{\mu\to e} \equiv \frac{N_e^{obs}}{\Phi_\mu^{exp}\cdot\sigma_e\cdot\varepsilon_e}. \qquad (3)$$

And, our observable is,

$$P'_{\mu\to e} \equiv \frac{N_e^{obs}}{N_\mu^{exp}} = P_{\mu\to e}\cdot\frac{\sigma_e}{\sigma_\mu}\cdot\frac{\varepsilon_e}{\varepsilon_\mu} = P_{\mu\to e}\cdot r_\sigma\cdot r_\varepsilon, \qquad (4)$$

where $r_\sigma = \sigma_e/\sigma_\mu$ and $r_\varepsilon = \varepsilon_e/\varepsilon_\mu$. Then, asymmetry asymmetry parameter is

$$A_{CP} \equiv \frac{P(\nu_\mu\to\nu_e)-P(\bar{\nu_\mu}\to\bar{\nu_e})}{P(\nu_\mu\to\nu_e)+P(\bar{\nu_\mu}\to\bar{\nu_e})} \qquad (5)$$

$$= \frac{P'/r_\sigma r_\varepsilon - \bar{P}'/\bar{r_\sigma}\bar{r_\varepsilon}}{P'/r_\sigma r_\varepsilon + \bar{P}'/\bar{r_\sigma}\bar{r_\varepsilon}} \qquad (6)$$

$$= \frac{P'-\bar{P}'}{P'-\bar{P}'}\left\{1+\frac{2\bar{P}'^2}{P'^2-\bar{P}'^2}\left(\frac{\bar{r_\sigma}-r_\sigma}{r_\sigma}+\frac{\bar{r_\varepsilon}-r_\varepsilon}{r_\varepsilon}\right)\right\}. \qquad (7)$$

So, we need to correct "fake" asymmetry due to the difference of cross sections and detection efficiencies between neutrino and anti-neutrino to see asymmetry from CP term. But, to do the correction, only the difference of r_σ, r_ε between neutrino and anti neutrino appear in the asymmetry parameter. Figure 3 shows the cross section ration (r_σ) of neutrino and anti neutrino. In the energy window of the experiment, r_σ is almost 1.0 and the difference between neutrino and anti neutrino is only a few percent level. Therefore, the uncertainty on CP phase measurement from the uncertainty of neutrino cross-section is rather small hence fake asymmetry due to cross sections can be corrected easily and safely.

Figure 4 shows the expected numbers of ν_e and $\bar{\nu_e}$ events for the case of $\sin^2 2\theta_{13}$=0.01(left), 0.05(center), 0.1(right). These figures are plotted assuming perfect background rejection and perfect correction of fake asymmetries due to cross sections and efficiencies. Another main source of fake asymmetry is a matter effect that is different in the case that $\Delta m^2 > 0$ ($m_3^2 > m_1^2, m_2^2$) and $\Delta m^2 < 0$ ($m_3^2 < m_1^2, m_2^2$). Fake asymmetry due to the matter effect become large for large θ_{13}. This asymmetry also need to be subtracted to see CP effect. In the case of small θ_{13} case like left figure, CP effect is larger than matter effect.

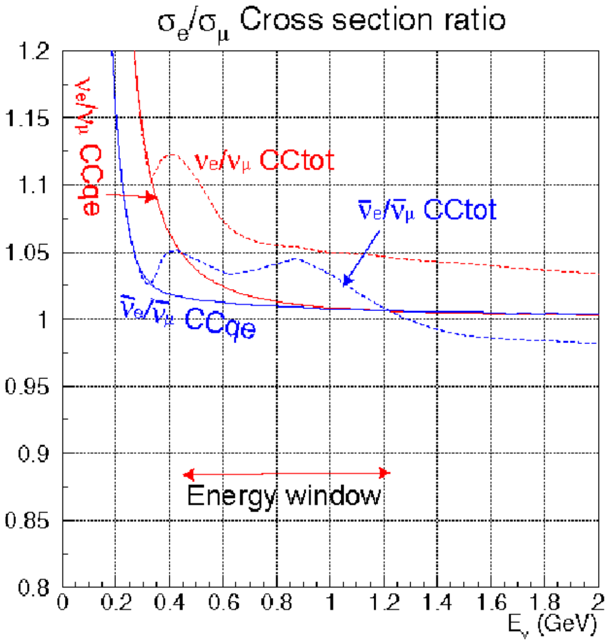

Figure 3. Cross section ratio of ν_e/ν_μ and $\bar{\nu_e}/\bar{\nu_\mu}$. Solid(dashed) lines are ratio of charged current quasi elastic interactions (charged current total) cross sections. As for the charged currents, the difference of ratio between neutrinos and anti neutrinos is less than 5% in the energy window of the experiment.

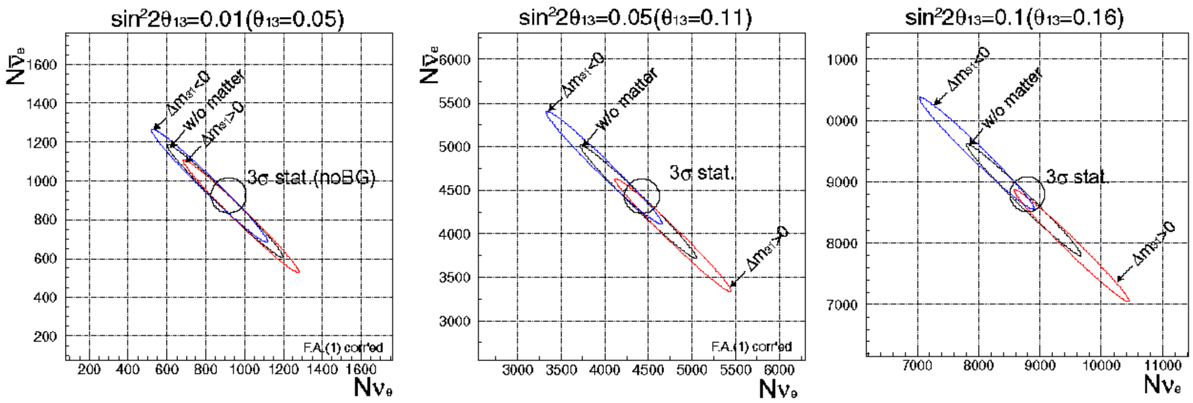

Figure 4. Expected numbers of oscillation signal ν_e and $\bar{\nu_e}$ for different scenario of θ_{13} value. Numbers after background subtraction and correction of fake asymmetry due to cross section difference are shown.

Finally, after the correction of matter effect, the sensitivity strongly depends on the background subtraction uncertainty. Figure 5 shows excepted sensitivity for some assumptions on background subtraction uncertainties. For present background level, one should reduce its uncertainty down to ~2% to measure down to $\sin\delta \sim 0.4$. Apparently, more powerful background rejection works well for good sensitivity. So, we should reduce both background level and background subtraction uncertainty.

4. Further improvements

As shown in previous section, high rejection and precise estimation of backgrounds are most important feature to realize the CP measurement. Present analysis tools of Super-Kamiokande and our knowledge so far need to be improved to measure the CP phase. There is some items for the improvement of sensitivity.

· ~90% of ν_μ backgrounds are due to π^0 production. Improvement of next generation detector: improvement of timing resolution, care of light scattering and reflection, or, segmented detector will help to identify π^0 and ν_e. Analysis software should be improved to reduce the background contaminations. Then, precise measurement of NC π^0 rate at front detector will reduce the uncertainty of background subtraction.

· ~50% of backgrounds are produced from ν_e contamination in the beam. So, we need to measure ν_e/ν_μ ratio at front detector to reduce background subtraction uncertainty. Another item to reduce ν_e background is to narrower the energy window by improving the resolution of neutrino energy measurement.

· ~50% of backgrounds are produced from neutrinos of higher energy (tail) of neutrino beam. If we can suppress the high energy tail, background level can be reduced well. There is some ideas to reduce high energy tail, for example, by adding a bending magnet between two horn magnets, we can expect to get much monochromatic pions

· wrong sign backgrounds are more serious for $\bar{\nu_\mu}$ beam run. Since charge identify of electrons in a water cherenkov detector is quite difficult, we should measure the contaminations of wrong sign neutrino. Magnetized detector may help the measurement. As another method, if we can measure recoiled neutron in the tank, we can reduce the uncertainty of measurement of wrong sign neutrino.

The studies of items listed above will help the precise measurement of oscillation probability so that enable the CP term measurement.

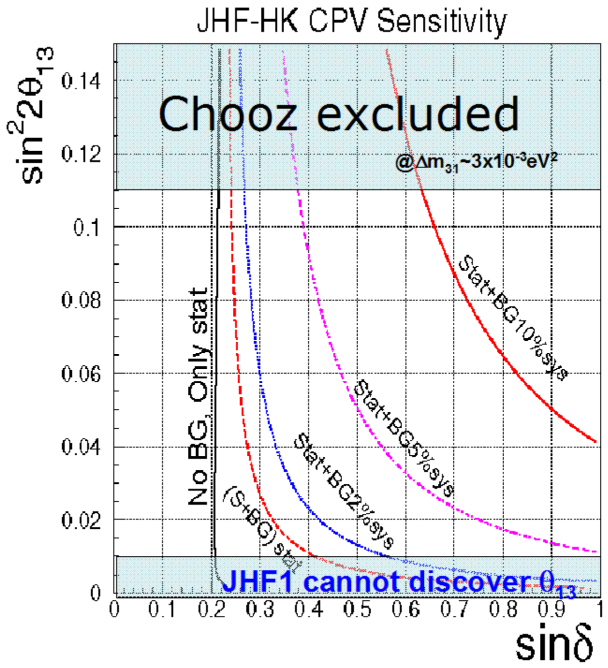

Figure 5. Expected sensitivity for $\sin\delta - \sin^2 2\theta_{13}$ space. From left to right, 3σ contours of no background case, perfect background subtraction case, background subtraction uncertainty is 2%, 5%, and 10% cases are shown.

5. Summary

The Second phase of JHF-Kamioka neutrino experiment is started its discussion that one of main subject is measure the CP phase of lepton sector.

Difference and uncertainty of cross sections of neutrino and anti neutrino make a fake asymmetry in the CP asymmetry (A_{CP}) measurement. But, major part of the cross section uncertainty can be canceled out by using the "difference of ratio" of cross sections in the calculation hence fake asymmetry due to cross section can be corrected safely.

Background subtraction ability and its uncertainty directly effect to the CP measurement sensitivity. The background subtraction level and its uncertainty should be improved before starting the experiment.

REFERENCES

1. Y. Itow *et al.*, "The JHF-Kamioka neutrino project", hep-ex/0106019.
2. Y. Fukuda *et al.*, Phys. Lett. B 433(1998), 9
3. Y. Fukuda *et al.*, Phys. Rev. Lett. 81(1998), 1562

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\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2S_{13}^2)\right) \\
&+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+ 4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&- 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2}{4E} \frac{aL}{4E} (1 - 2S_{13}^2)
\end{aligned} \tag{1}
$$

Table 1
Numbers of signal and background neutrino events expected to be observed as ν_e ($\bar{\nu_e}$) interaction by 450 kilotons fiducial volume water cherenkov detector at Kamioka site. Numbers between brackets are the events with π^0 production. Assumed oscillation parameter set is: $\Delta m_{12}^2 = 5 \times 10^{-5} eV^2$, $\Delta m_{23}^2 = 3 \times 10^{-3} eV^2$, $\sin^2 2\theta_{13} = 0.03$, $\sin^2 2\theta_{23} = 1$, $sin^2 2\theta_{12} = 0.8$, and $\delta = 45°$. Assumed beam time is 5×10^{21} p.o.t. ($\sim$ 1 year run of 4MW accelerator) for ν_μ beam and 1.83×10^{22} p.o.t. ($\sim$ 3.66 year run) for $\bar{\nu_\mu}$ beam.

	Signal		Backgrounds				
Beam	signal ν_e w/o CP	Effect of CP	ν_μ	ν_e	$\bar{\nu_\mu}$	$\bar{\nu_e}$	total
ν_μ	699	-123	241(223)	225(13)	34(28)	11(1)	510(264)
$\bar{\nu_\mu}$	699	+120	238(213)	164(16)	342(302)	210(8)	953(540)