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Long baseline neutrino experiments

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Abstract. In this talk I review the physics that can be done at accelerator-based long baseline neutrino experiments, both current and future (those under construction and those that are proposed).

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1. Introduction

Solar neutrino experiments (Homestake, Kamiokande, GALLEX, SAGE, Super-Kamiokande, SNO and GNO) show that 2/3 of $\nu_{\rm e}$ from the Sun are being converted into ν_μ/ν_τ. SNO neutral current rate measurement is the key measurement which shows that the conversion is into active flavours [1]. Neutrino oscillations provide the most elegant explanation of all the data [2].

$$\Delta m^2_{\rm sol} = 7^{+5}_{-1.3} \times 10^{-5}\ {\rm eV}^2,$$
$$\tan^2\theta_{\rm sol} = 0.4^{+0.14}_{-0.1}. \tag{1}$$

Atmospheric neutrino experiments (IMB, Kamiokande, Super-Kamiokande (SK)) show that ν_μ created in cosmic ray interactions with atmospheric nuclei are being converted into ν_τ but $\nu_{\rm e}$ created in such interactions are unaffected. SK measurement of ν_μ and $\nu_{\rm e}$ event rates as functions of zenith angle is the key measurement in establishing this result. Once again neutrino oscillations provide excellent fit to the data [3]

$$\Delta m^2_{\rm atm} = 2.0^{+1.0}_{-0.7} \times 10^{-3}\ {\rm eV}^2,$$
$$\sin^2 2\theta_{\rm atm} \geq 0.92. \tag{2}$$

Recently SK has also observed a dip in the L/E spectrum of their muon data [4], which is predicted by oscillations. The position of the dip is consistent with the $\Delta m^2_{\rm atm}$ obtained from the SK analysis of zenith angle dependence of muon event rates.

From the above experimental evidence it can be concluded that neutrino flavour conversion is established conclusively but the mechanism of conversion is not established unambiguously. Neutrino oscillations provide the most elegant (and theoretically consistent) explanation to the data. The goals of future neutrino experiments are

- to obtain unambiguous evidence for neutrino oscillations,
- to measure the parameters of oscillation accurately,

using man-made neutrino sources (reactors for $\bar{\nu}_{\rm e}$ and accelerators for ν_μ or $\bar{\nu}_\mu$).

If we assume that only two flavours ν_α and ν_β mix, the flavour survival probability is

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E), \tag{3}$$

where L is the distance between the source and the detector and E is the neutrino energy. Observing the predicted variation in L or E will provide conclusive evidence for neutrino oscillations. All the neutrino sources generate neutrinos with a spread in energy. Hence all the experiments attempt to detect the neutrinos as a function of neutrino energy and observe the minimum predicted at $E_{\pi/2} = \pi\Delta m^2 L/2.54$.

2. Three flavour oscillations

Since there are three neutrino flavours, we must consider mixing between all three in interpreting the data,

$$\begin{bmatrix} \nu_{\rm e} \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}. \tag{4}$$

Mass eigenstates ν_i have masses m_i. Unitary matrix U is parametrized by three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and a phase δ. Oscillation probabilities depend on these four parameters and two mass differences $\Delta_{21} = m_2^2 - m_1^2, \Delta_{31} = m_3^2 - m_1^2$.

CHOOZ experiment limits $\sin^2 2\theta_{13} \leq 0.1$ [5]. In the limit of small θ_{13}, we have [6]

$$\begin{aligned} &\Delta m^2_{\rm sol} \simeq \Delta_{21} \quad \theta_{\rm sol} \simeq \theta_{12}, \\ &\Delta m^2_{\rm atm} \simeq \Delta_{31} \quad \theta_{\rm atm} \simeq \theta_{23}. \end{aligned} \tag{5}$$

From the above we note that $\Delta_{21} \ll \Delta_{31}$. Matter effects in LMA solution of solar neutrino problem require Δ_{21} to be positive. But sign of Δ_{31} cannot be determined from present data.

Nuclear reactors emit very large fluxes of $\bar{\nu}_{\rm e}$ with an energy range 1–8 MeV. These neutrinos can be used to determine Δ_{21} and θ_{12} accurately. KamLAND is such an experiment [7] which has been taking data for the past three years. This experiment has observed both the flux suppression and spectral distortion caused by neutrino oscillation and obtained very strong constraint on Δ_{21},

$$\begin{aligned} &\Delta_{21} = 8.2 \pm 0.6 \times 10^{-5}\ {\rm eV}^2, \\ &\tan^2\theta_{21} = 0.1 - 10. \end{aligned} \tag{6}$$

New nuclear reactor-based neutrino experiments are proposed to

- reduce the uncertainty in θ_{12}. These experiments are expected to have a baseline of about 60 km so that the $E_{\pi/2}$ minimum corresponding to Δ_{21} occurs at 4 MeV,
- measure θ_{13}. These are very high statistics experiments with a baseline of about 2.5 km so that the $E_{\pi/2}$ minimum corresponding to Δ_{31} occurs at 4 MeV [8].

3. Goals of long baseline neutrino experiments

- To observe a minimum of $P(\nu_\mu \to \nu_\mu)$ which occurs when $1.27\Delta_{31}L/E = n\pi/2$, where n is an integer.
- To determine the energy where the minimum occurs accurately (this determines Δ_{31} accurately).
- To measure $P(\nu_\mu \to \nu_\mu)$ at the above minimum accurately (this determines $\sin^2 2\theta_{23}$).
- To observe $P(\nu_\mu \to \nu_{\rm e})$ oscillations and measure θ_{13}.
- To observe $\nu_\mu \to \nu_\tau$ oscillations by reconstructing the τ produced by ν_τ interaction.
- To detect evidence for matter effect and determine sign of Δ_{31}.
- To observe CP violation and determine δ.

These aims can be achieved using accelerator neutrino beams [9] which are high energy, almost pure ν_μ beams with about 1% $\nu_{\rm e}$ component and even smaller fractions of $\bar{\nu}_\mu$ and $\bar{\nu}_{\rm e}$. Large fluxes can be produced by increasing the current of the initial proton accelerator. The energy of the beam can be varied by tuning the energy of the proton and focussing. In addition, sharply peaked spectrum, with a very small spread in energy can be obtained by locating the detector at a location a few milliradians off the axis of the main beam offaxis. Experiments usually consist of a small near-end (1 km) detector, which measures the unoscillated flux and a large far-end detector. They can measure $P(\nu_\mu \to \nu_\mu)$ and $P(\nu_\mu \to \nu_{\rm e})$ as a function of neutrino energy. Accelerators can also produce pure $\bar{\nu}_\mu$. They may be needed in the search matter effects (if Δ_{31} is negative) and for evidence for CP violation. Since $\bar{\nu}_\mu$ cross-section is only about a third of ν_μ cross-section, the running time will be three times larger for the same statistical accuracy.

4. Long baseline neutrino experiments

K2K: $L = 250$ km, in progress. Measured $P(\nu_\mu \to \nu_\mu)$ vs. E and observed energy dependent deficit of ν_μ flux.
Number of events in case of no oscillations ($N_{\rm NO}$) = 50/year.

MINOS: $L = 730$ km, under construction.
Expected data taking: 2005. $N_{\rm NO} = 300$/year.
Can detect neutral current event rate of ν_μ. Difficult to measure $P(\nu_\mu \to \nu_{\rm e})$ and so sensitivity to θ_{13} is not very good.

OPERA: $L = 730$ km. No near detector.
Searches for $\nu_\mu \to \nu_\tau$ signal.

ICARUS: $L = 730$ km. No near detector.
Can search for both $P(\nu_\mu \to \nu_e)$ and $P(\nu_\mu \to \nu_\tau)$.

J2K: $L = 295$ km, under construction.
Expected data taking: 2009. High statistics experiment with $N_{NO} = 3000$/year.
Can measure $P(\nu_\mu \to \nu_e)$. So good sensitivity to θ_{13} and CP violation but not to matter effects.

BNL to Homestake: $L = 2540$ km, being planned.
Ultimate accelerator beam experiment with very high statistics with $N_{NO} = 3000$/year.
Can achieve all the goals listed above with a little bit of luck.

4.1 *K2K*

In this experiment, which has a baseline of 250 km, the ν_μ beam from KEK is directed to Super-K detector. Quasi-elastic events $\nu_\mu + n \to \mu^- + p$, with $E_\mu > 200$ MeV are observed and the energy of the neutrino reconstructed. This is a low statistics experiment. The expected number of events in case of no oscillations is only about 50 per year. Data taking started in 1999 and, so far, 427 days of data have been collected. For this period, the expected number of quasi-elastic events is 85 ± 9 and the observed number is 57. Best-fit parameters coincide with atmospheric neutrino parameters [11]. K2K can, in principle, observe $\nu_\mu \to \nu_e$ oscillations by the detection of quasi-elastic events $\nu_e + n \to e^- + p$. But the flux is too low to give any useful information on θ_{13} [12].

4.2 *MINOS*

This is a high-statistics experiment under construction with ν_μ beam from Fermilab directed to SOUDAN mine, with a baseline of 731 km. The beam is broad band with neutrino energy varying from 1 to 10 GeV. The detector is a magnetized iron calorimeter with good energy reconstruction capability. The main signal events are CC DIS interactions $\nu_\mu + N \to \mu^- + X$. These are identified by high energy muon in the detector.

For $\Delta_{31} = 2\times10^{-3}$ eV^2, the oscillation minimum corresponding to $1.27\Delta_{31}L/E = \pi/2$, occurs at $E = 1.2$ GeV. Flux is too small at this energy for the minimum to be clearly established. By looking at the shape of $P(\nu_\mu \to \nu_\mu)$ at larger energies, MINOS expects to measure Δ_{31} and $\sin^2 2\theta_{23}$ to about 10% accuracy. Figure 1 shows the expected distribution of muon events as a function of neutrino energy for two different values of Δ_{31}. MINOS can also detect NC DIS events $\nu + N \to \nu + X$. Events without a high-energy muon are classified NC events. Measurement of this rate can verify that ν_μ is oscillating into active flavours. $\nu_\mu \to \nu_e$ oscillations lead to $\nu_e + N \to e^- + X$ events in the detector. Identifying a high-energy electron in the detector is difficult. Various efforts are being made to improve the electron

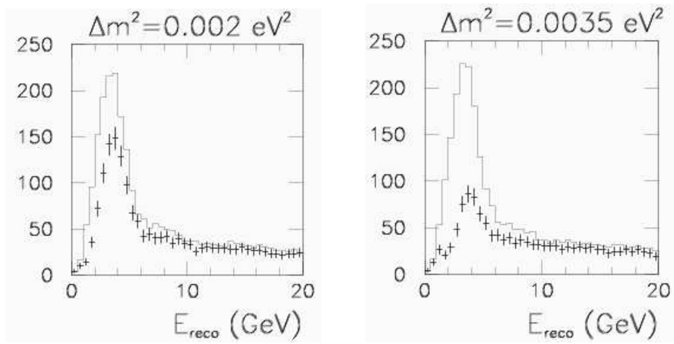

Figure 1. Expected event rate spectrum at MINOS for two different values of Δ_{31}. $\sin^2 2\theta_{23}$ is assumed to be 1.

identification in the detector but the NC events form a huge background to the $\nu_\mu \to \nu_{\rm e}$ oscillation signal. So the sensitivity of MINOS to $\sin^2 2\theta_{13}$ is not very good. It can improve the CHOOZ limit by a factor 2 [13].

4.3 *OPERA and ICARUS*

Both these experiments will be located at Gran Sasso and will receive ν_μ beam from CERN, which corresponds to a baseline of 730 km. Since these experiments are searching for τ appearance via $\nu_\mu \to \nu_\tau$ and $\nu_\tau + N \to \tau + X$, the energy of the beam is quite high ($E \simeq 15$ GeV), well above τ production threshold. There is no near detector to monitor neutrino flux [14].

OPERA is an emulsion experiment which seeks to detect τs produced in ν_τ interactions which follow $\nu_\mu \to \nu_\tau$ oscillations. For the best-fit parameters given by atmospheric neutrino analysis, 10 clean events are expected in five years time.

ICARUS uses liquid argon as detector material and has the capability to identify both electrons and muons. It can search for $\nu_\mu \to \nu_\tau$ by observing the semi-leptonic decays (into electrons or muons) of the τs. Twelve clean τ events are expected in five years time. The good electron identification capability enables it to detect $\nu_\mu \to \nu_{\rm e}$ oscillations but the event rates at higher energies are rather small. Lower limit on θ_{13} can be improved to 6° (similar to MINOS).

4.4 *J2K*

This is a very high statistics experiment that is expected to start taking data in 2009. At the same time the high intensity proton synchrotron at Japan Hadron Facility (JHF) is completed. In this experiment, the high intensity ν_μ beam from JHF is directed to Super-Kamiokande (SK) detector 295 km away. The neutrino flux is about 100 times the flux of beam from KEK. The number of ν_μ charged current events expected, in the case of no oscillations, is about 3100 per year.

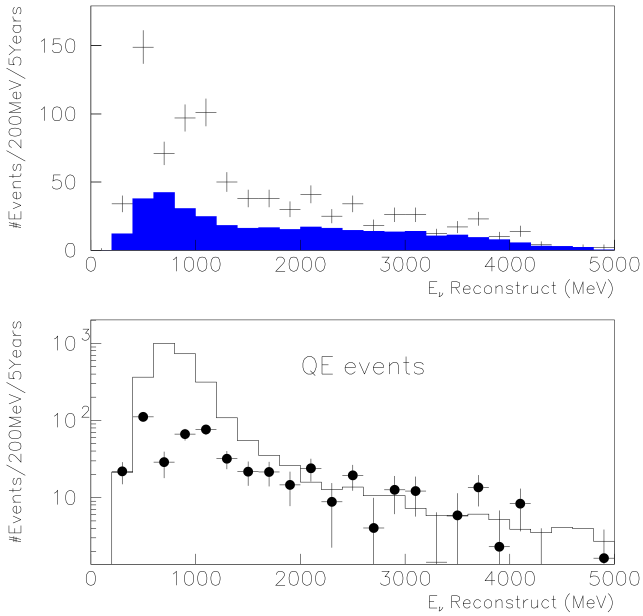

Figure 2. The neutrino energy spectrum expected in SK detector for five years of exposure of JHF 2° off-axis beam. The events with oscillation are generated with $\Delta_{31} = 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

The neutrino beam-line is designed so that the SK detector is about 2° off-axis. Due to this design, the flux at SK site peaks in the energy range 0.6–0.8 GeV, which enables it to be sensitive to values of Δ_{31} even smaller than 2×10^{-3} eV^2.

J2K detects quasi-elastic events $\nu_\mu + n \to \mu^- + p$, with $E_\mu > 200$ MeV. Since the original neutrino direction and final lepton energy and direction are known, J2K can reconstruct the original neutrino energy accurately. Figure 2 shows the expected distribution of quasi-elastic (QE) muon events vs. reconstructed neutrino energy both for the case of no oscillations and oscillations. J2K is capable of observing the minimum in $P(\nu_\mu \to \nu_\mu)$ for Δ_{31} as small as 2×10^{-3}. For this value of Δ_{31}, the expected accuracy in the measurement of Δ_{31} and $\sin^2 2\theta_{23}$ is better than 5%. If Δ_{31} is a little larger ($\simeq 2.5 \times 10^{-3}$ eV^2), then the accuracy can be as good as 1%. The expected precision in the determination of neutrino parameters at J2K is shown in figure 3.

J2K can also detect quasi-elastic events $\nu_{\rm e} + n \to e^- + p$ and so is quite sensitive to θ_{13}. It can improve the lower limit on $\sin^2 2\theta_{13}$ to 0.01 (factor of 10 better than CHOOZ). It can observe a signal for $\nu_\mu \to \nu_{\rm e}$ oscillations if $\theta_{13} > 4°$. Because of the short distance, it is not sensitive to matter effects [15].

To summarize, J2K can achieve the first two goals of long baseline neutrino experiments, that is, measuring Δ_{31} and θ_{23} with good precision. However, these goals can be achieved only if $\Delta_{31} \geq 10^{-3}$ eV^2, as we presently expect from atmospheric neutrino studies. A measurement of θ_{13} is possible only if $\theta_{13} \geq 4°$. Matter

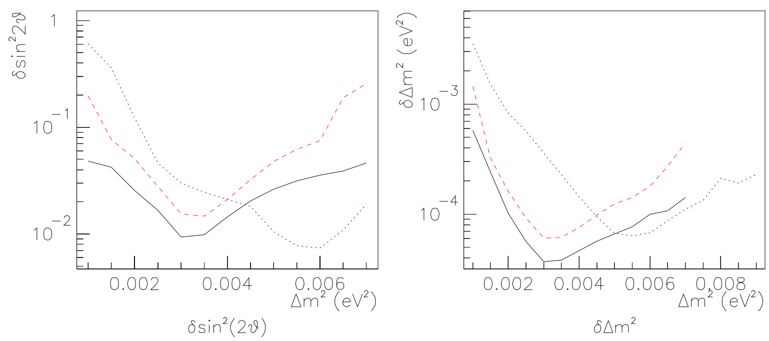

Figure 3. Expected precision in the determination of Δ_{31} and of $\sin^2 2\theta_{23}$ as a function of Δ_{31}. Here the input of value of $\sin^2 2\theta_{23}$ is taken to be 1.

effects and the sign of Δ_{31} are not possible because of the short baseline. There are plans to conduct CP-violation studies by increasing the event rate by a factor of 100. This is hoped to be achieved by boosting the flux by a factor of 5 and building Hyper-Kamiokande, which will be 20 times larger than SK [16]. In such a situation, CP violation, due to as small values of $\delta_{\rm CP}$ as 20°, will be measurable.

4.5 *BNL to Homestake*

This recently proposed experiment is capable of achieving all the goals of long baseline neutrino experiments. In this experiment ν_μ beam from Brookhaven is to be aimed at 0.5 megaton water Cerenkov detector located at Homestake or some other suitable site with a baseline of about 2500 km. This proposal is a realization of the superbeam experiments proposed by Richter [9] with very long baselines and very high statistics. The expected number of events in case of no oscillations is about 3000 per year. The water Cerenkov detector can detect both muon and electron events. The neutrino beam energy is in the range 0.5–6 GeV.

This experiment is capable of observing the minimum in $P(\nu_\mu \to \nu_\mu)$ for Δ_{31} as small as 0.5×10^{-3} and hence is capable of measuring Δ_{31} and $\sin^2 2\theta_{23}$ to 2% accuracy or better. The expected distribution of muon events vs. neutrino energy for the case of no oscillations and oscillations is shown in figure 4. Figure 5 shows the precision with which this experiment can measure Δ_{31} and $\sin^2 2\theta_{23}$.

From the electron events, one can

- measure $\sin^2 2\theta_{13}$ as small as 10^{-3} (factor 10 better than J2K),
- determine sign of δ_{31} using purely ν_μ beam,
- measure the CP-violating phase δ using purely ν_μ beam.

Including matter effects, we have

$$P(\nu_\mu \to \nu_{\rm e}) = \sin^2\theta_{23}\sin^2 2\theta^m_{13}\sin^2(1.27\Delta^m_{31}L/E),$$

where

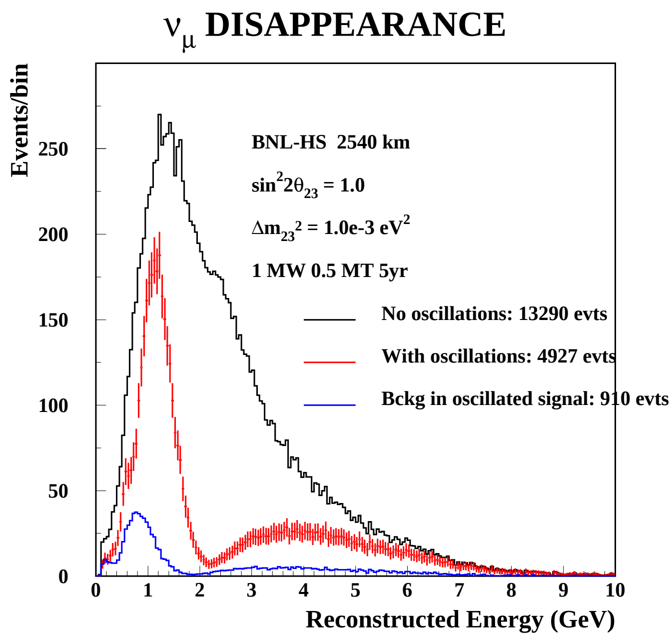

Figure 4. Event rate spectrum for $\Delta_{31} = 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$.

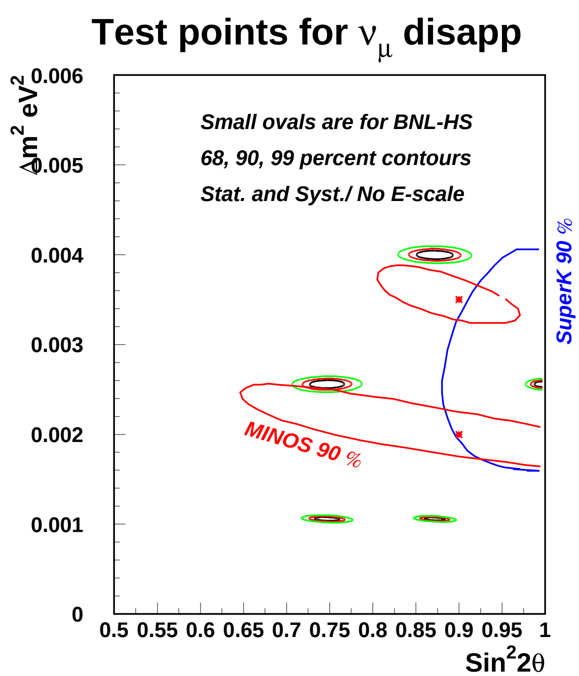

Figure 5. Precision expected in the determination of Δ_{31} and $\sin^2 2\theta_{23}$.

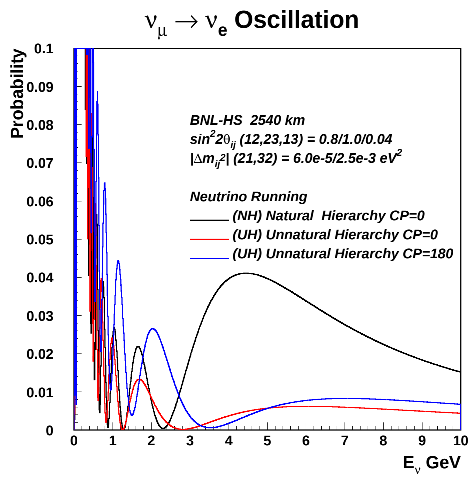

Figure 6. Matter dependent $P(\nu_\mu \to \nu_{\rm e})$ for positive Δ_{31} (natural hierarchy) and negative Δ_{31} (inverted hierarchy).

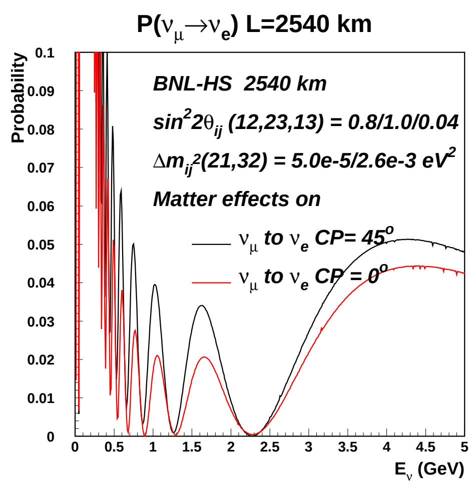

Figure 7. Change in $P(\nu_\mu \to \nu_{\rm e})$ due to the CP phase $\delta_{\rm CP}$.

$$\sin^2 2\theta_{13} = \sin^2 2\theta_{13}\Delta_{31}/\Delta_{31}^m,$$
$$\Delta_{31}^m \simeq |\Delta_{31} - A|.$$

Hence $\sin^2 2\theta_{13}^m$ keeps increasing with energy until $A \simeq \Delta_{31}$. This energy cut-off is about 10 GeV. For events in the energy range 3–7 GeV, matter effects boost the signal by a factor of 2 if Δ_{31} is positive and suppress by the same factor if Δ_{31} is negative. Figure 6 illustrates the change induced by matter effects in $P(\nu_\mu \to \nu_{\rm e})$ probability. In this energy range, effect of the CP phase $\delta_{\rm CP}$ is non-negligible but small.

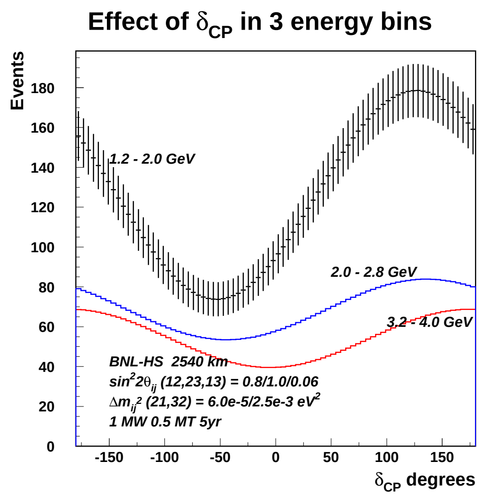

Figure 8. Sensitivity of different energy ranges to CP phase.

On the other hand, in the energy range 1–3 GeV, the event rates are more sensitive to CP phase and are essentially insensitive to matter effects. So by dividing the number of events into these two energy bins, one can observe matter effects and measure CP phase δ_{CP} using only neutrino beams. This is illustrated in figures 7 and 8. This is certainly advantageous because the neutrino interaction rates are three times larger than the anti-neutrino interaction rates. Note that, for an unambiguous signal for CP violation one requires data from both ν_μ and $\bar{\nu}_\mu$ beams. However, the measurement of CP phase, with the assumption of three flavour mixing a la CKM, can be done with pure neutrino beam in this experiment [17].

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