Super muon-neutrino beams: Physics reach and open questions

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Abstract. High intensity conventional horn-focused neutrino beam produced by MW-class proton accelerator, "superbeam", provides opportunity to further develop neutrino physics, especially long baseline (LBL) oscillation experiments. Several superbeam LBL experiments are proposed as next generation high sensitivity, high precision experiments before neutrino-factory era. Sensitivities of the experiments are one or two orders of magnitude higher than the current ones. The experiments and their physics potential are introduced.

1. Introduction

The evidence of neutrino oscillation in the atmospheric neutrinos discovered by Super-Kamiokande (SK) [1] is being confirmed by the first accelerator-based long baseline (LBL) oscillation experiment, K2K [2]. Also, implications of neutrino oscillation in the solar neutrino [3] is now confirmed by a reactor-based LBL experiment, KamLAND [4]. Existence of finite neutrino masses and large flavor mixing becomes almost unambiguous. They are the first observations which are contrary to the standard model.

The neutrinos have anomalously small masses compared with quarks and other leptons. The See-Saw mechanism try to explain the smallness by introducing right-handed heavy Majorana neutrino [5]. The large mixing found in the neutrino sector is very much different from the small mixing in the quark sector. Grand Unified Theories, which describes quarks and leptons in a unified manner at ultra-high energy scale, relate the mixings of quark and lepton sectors. Precise knowledge on these neutrino properties would provide a big hint of the physics beyond the standard model.

Next step in LBL experiments along this direction is to establish (or refute) the framework of 3-flavor mixing. One of the most important things for that purpose is to discover the only remaining oscillation mode $\nu_\mu \to \nu_e$ or finite mixing angle θ_{13}. The mixing angle is known to be much smaller than the other two mixing angle [**?**]. Discovery and precise measurement of θ_{13} would provide a key to explore the physics at high energy scale. It is also important to measure oscillation parameters precisely by checking the spectrum shape after oscillation. Deviation from the predicted oscillation pattern would imply non-standard model physics, such as extra dimension. Furthermore, firm confirmation of $\nu_\mu \to \nu_\tau$ oscillation by (1)direct observation of ν_τ or (2) observation of neutral current interactions are also important. This would provide a constraint on sterile neutrino. Once the finite θ_{13} is found, search for the CP

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violation in the lepton sector becomes realistic. Since the large mixing angle region is found to be the solution of the solar neutrino problem, the expected size of the CP asymmetry is within the reach of the next generation LBL experiments provided that θ_{13} is not extremely small. Discovery of the CP violation in the lepton sector would be a big step to understand matter anti-matter asymmetry in the universe.

One or two order of magnitude higher intensity neutrino beam than current on-going experiment is necessary to achieve the purposes. Several high statistics LBL experiments with conventional horn-focused ν_μ beam produced by a MW-class proton accelerator are being proposed. Such attempts are recently called "superbeam" experiments, when it is contrasted from LBL experiments with neutrino factory. In my presentation, the proposed superbeam experiments and their physics potential are summarized.

2. Super-beam experiments

2.1. Project in Japan: JHF-Kamioka project

In Japan, construction of a MW proton accelerator complex, now called as J-

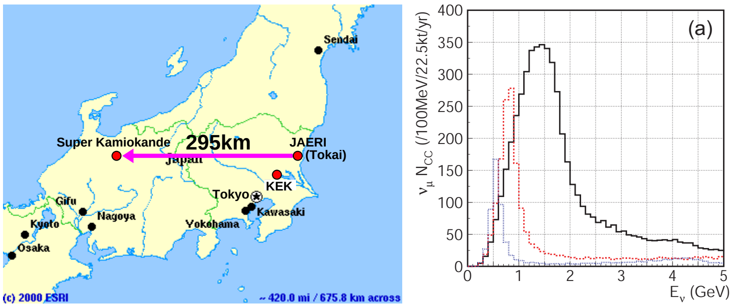

Figure 1. (Left) Locations of JAERI-Tokai site and SK. (Right) Expected spectrum of CC interactions at SK. The solid (black), dashed (red) and dotted (blue) histograms are OA1.5°, OA2° and OA3°, respectively. ‖

PARC, is going on at JAERI-Tokai site aiming the completion by March, 2007 [7]. Using the 50 GeV proton synchrotron in J-PARC, a long baseline neutrino oscillation experiment is being planned. (The 50-GeV related facilities in the project are still called as JHF.) At the first phase of the project, the power of the 50 GeV PS is 0.75 MW and SK will be used as a far detector. The intensity of the neutrino beam is expected to be about 2 orders of magnitudes higher than K2K. Locations of JAERI and SK is shown in Fig. 1. The baseline length between JAERI and SK is 295 km. In the second phase, we plan to use upgraded 4-MW PS and 1-Mt "Hyper-Kamiokande"[9].

The goals of the first phase are the precision measurements of oscillation parameters in ν_μ disappearance and discovery of ν_e appearance. Also, $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$ oscillation can be tested by measuring number of NC interactions in SK. The features of the experiment can be summarized as follows:

(i) Use of low-energy narrow-spectrum neutrino beam tuned at oscillation maximum in order to maximize the sensitivity. The baseline length of 295 km corresponds to the oscillation maximum of $E_\nu \simeq 700$ MeV when $\Delta m^2 = 3 \times 10^{-3}$ eV^2.

(ii) Use of "off-axis"(OA) configuration to produce the highest possible intensity with a narrow energy spread [10]. To adjust the peak of the neutrino spectrum at oscillation maximum, the OA angle will be at $2 \sim 3$ degree.

(iii) Use of gigantic water Čerenkov detector (SK) as a far detector. SK has excellent performance in detecting low-energy neutrinos.

(iv) Neutrino energy of each event is reconstructed from momentum of a charged lepton in charged current quasi elastic (CCqe) interaction, $\nu_l + n \rightarrow l^- + p$. The energy resolution in this method is as good as ~ 80 MeV. Since the CCqe reaction dominates in the sub-GeV region, efficient and clean measurement of neutrino energy spectrum is possible.

Technical design of the neutrino facility is in progress [11]. Expected numbers of interactions at SK with 2° OA are about 4500 (3000) for total (CC) interactions in fiducial volume of 22.5 kt in 1 year. The expected ν_μ spectrum at SK without oscillation is plotted in Fig. 1. One of the critical issue in searching for ν_e appearance is intrinsic ν_e contamination in the beam which comes from μ and K decay. The ν_e to ν_μ flux ratio is as small as 0.2% at the peak energy of ν_μ spectrum.

In order to monitor the neutrino beam and to predict the flux and spectrum at SK as precisely as possible, muon monitor behind the beam dump and front neutrino detector at 280 m from the production target will be installed. In addition, possibility of placing a neutrino detector at $\gtrsim 1.5$ km from the target is being seriously discussed. At these distances, neutrino spectrum becomes almost identical to that at SK. This could eliminate one of the largest systematic uncertainties in LBL experiments, i.e., spectrum difference between far and near site.

2.2. Projects in US

In US, the MINOS experiment is now under construction, in which ν_μ beam is produced by the proton beam from Main Injector (MI) at FNAL and detected by a detector which is being constructed in Soudan mine, 730km from FNAL. The proton beam intensity from MI is 0.4MW. Recently, possibilities to upgrade the power of the beam [12] and to construct an "off-axis" detector [13] are being seriously discussed to conduct next-generation high-sensitivity LBL experiments.

The intensity upgrade is an idea to replace the current 8-GeV booster by a rapid-cycling high-intensity 16-GeV synchrotron. It increases intensity in the MI by a factor of four, i.e. to 1.6 MW [12]. In the long term, upgrade to 4 MW is also envisaged by adding a 600 MeV linac and a 3 GeV pre-booster. Improvement in the precision of NuMI experiment is expected by the upgrade.

New OA detector(s) are proposed to exploit the full potential of the NuMI neutrino beam and to complement the MINOS experiment [13]. The main goal of the proposal in the first phase is to search for ν_e appearance with a detector of the order of 20-kt fiducial mass. In the second phase, with the increased beam intensity by the Proton Driver and increase of the detector mass by about factor of five, higher sensitivity search of ν_e appearance or a measurement of CP violation would be possible.

The expected spectra at off axes are shown in Fig. 2. The possible sites for the detector is being investigated. The distances from FNAL to the candidate sites ranges from 600 to 900 km. Low-Z tracking calorimeter is mainly being studied as a far detector while the other options, water-Cherenkov or liq. Ar TPC are still kept. In order to achieve good electron identification, sampling frequency of $1/4 \sim 1/3$ X_0 (radiation length) is being discussed in the case of the tracking calorimeter. The expected energy resolution is estimated to be about 16% for the energy range $1 \sim 3$ GeV by Monte-Carlo simulation assuming $1/3X_0$ sampling.

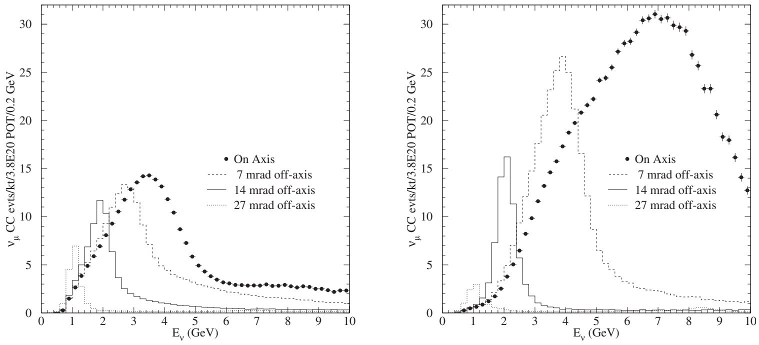

Figure 2. Energy spectra of CC events expected at a far detector location 735km from FNAL at various OA angles for the NuMI low-energy beam setting (left) and the medium-energy setting (right) [13].

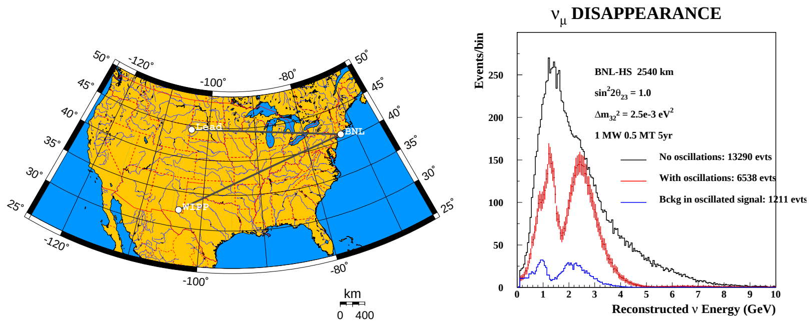

Figure 3. (Left) Locations of BNL and possible detector sites Homestake and WIPP at 2540 and 2880 km from BNL, respectively. (Right) Expected spectrum of detected events in a 0.5 MT detector at 2540 km from BNL including quasielastic signal and CC-single pion background with 1.0 MW of beam power in 5 years of running. The top histogram is without oscillations; the middle error bars are with oscillations and the bottom histogram is the contribution of the background to the oscillated signal only. This plot is for $\Delta m^2_{32} = 0.0025\ e\mathrm{V}^2$.

There is another interest to conduct a (very) long baseline experiment using a proposed beam from BNL [14]. The neutrino beam is produced by 28 GeV proton beam from Alternating Gradient Synchrotron (AGS) at BNL and is detected by huge water Cherenkov detector of 500 kt or more at more than 2000 km. The primary purposes are precise determination of oscillation parameters, search for ν_e appearance and CP violation. This idea consists of (1) Intensity upgrade of AGS from 0.14 MW to 1 MW, (2) Construction of new neutrino beam line (3) Construction of underground water Cherenkov detector of 0.5Mt fiducial mass. The locations of BNL and possible detector sites and expected neutrino spectra are shown in Fig. 3.

2.3. Projects in Europe

In Europe, there is an idea of superbeam LBL experiment in which the neutrino beam is produced by Super Proton Linac (SPL) and detected by a detector at Modane laboratory in Furejus tunnel, 130 km from CERN [15]. The proposed SPL is a 2.2 GeV linac with 4 MW beam power operated at 75-Hz repetition rate and 1.5×10^{14} protons/pulse. The neutrino beam is a conventional wide-band beam and the expected neutrino spectrum at the detector site is plotted in Fig. 4. The expected neutrino

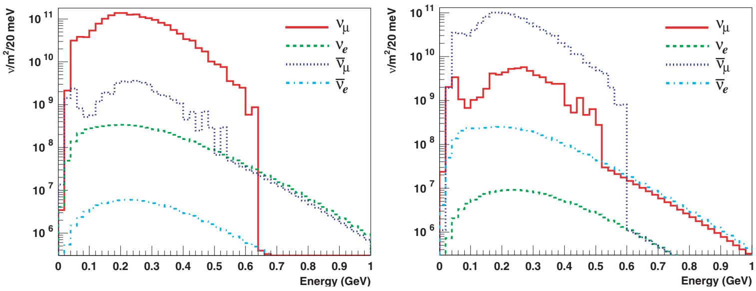

Figure 4. Spectrum of neutrino beam from CERN SPL.

spectrum ranges $\lesssim$ 500 MeV which matches with with the oscillation maximum of $\sim$ 300 MeV at $\Delta m^2 = 3 \times 10^{-3}$ eV^2. Currently two types of detector technology are under consideration, i.e., water Cherenkov detector of SK type and liquid scintillater detector of LSND/MiniBooNE type. The detector fiducial mass is supposed to be 40 kt.

2.4. Summary of experiments

Current and planned (superbeam) LBL experiments are summarized in Table 1. As can be seen in the $L/L_{\rm osci}$ column, neutrino energy and the baseline length in most of the superbeam experiments are chosen so that the neutrino energy matches at the oscillation maximum. Expected number of interactions in the superbeam experiments is more than 2 order of magnitude higher than current on-going experiment, K2K.

Table 1. Summary of (super)beam LBL experiments. The column "FM" is the fiducial mass of far detector. The letters in "status" column mean "A": accelerator, "B": neutrino beam line, "D": far detector, and the meaning of the symbols are ◎: in operation, ◯: construction, △: design.

	E_p (GeV)	Power (MW)	E_ν (GeV)	L (km)	$L/L_{\rm osci}$	FM (kt)	#CCint (/yr)	status A	B	D
K2K	12	0.005	1.3	250	0.47	22.5	30	running		
MINOS	120	0.4	3.5	730	0.51	5.4	2.5k	start 2005		
ICARUS/OPERA	400	0.3	17	732	0.10	2.35/1.65	6.5k/4.6k	start 2006		
JHFν	50	0.75	0.7	295	1.02	22.5	3k	◯	△	◎
OA-NuMI	120	0.4	2.0	700	0.89	20	2.4k	◎	◯	△
JHFνII	50	4.0	0.7	295	1.02	540	480k	△	△	△
Super-AGS	28	1.3	1.5	2540	4.1	500	16k	△	△	△
SPL-Furejus	2.2	4.0	0.26	130	1.21	40	650	△	△	△

*1 : The definition of neutrino oscillation length is $L_{osci.} = \frac{\pi}{2} \cdot \frac{<E_\nu>}{1.27\Delta m^2}$ for Δm^2 = 3$\times$10^{-3} eV^2.

3. Sensitivity

The proposed experiments with a superbeam have similar sensitivity for physics. Here, the physics sensitivities in the JHF-Kamioka project is mainly presented in detail. The results are based on full detector simulation of already existing far detector, SK.

3.1. ν_μ *disappearance*

The precision measurement of oscillation parameters θ_{23} and Δm^2_{23} is done by precisely measuring the spectrum distortion in ν_μ disappearance mode. In SK, fully contained events with single μ-like ring are selected to enhance the ν_μ CCqe events. In Fig. 5, expected distributions of reconstructed E_ν are shown for both without and with oscillation. Significant deficit in peak region is seen even without subtraction of

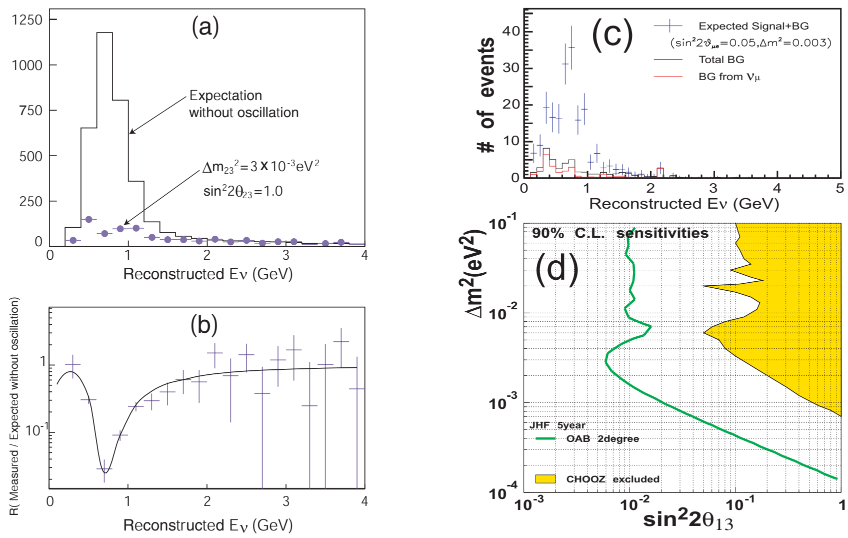

Figure 5. (a) Reconstructed muon neutrino energy spectrum in the case of $(\Delta m^2_{23}, \sin^2 2\theta_{23}) = (3 \times 10^{-3}\text{eV}^2, 1.0)$, compared with the null-oscillation case, (b) ratio of the measurement-to-expectation in the case of without oscillation (OAB 2°, 5-year measurements). (c) Reconstructed neutrino energy spectrum for FC 1R e-like events for 5 years of operation with OAB 2°. (d) Expected 90% sensitivity contour on $(\Delta m^2\ ,\sin^2 2\theta_{\mu e})$ compared with the CHOOZ exclusion plot, where $\sin^2 2\theta_{\mu e} \simeq 1/2 \cdot \sin^2 2\theta_{13}$ $(\theta_{23} = \pi/4)$ is assumed.

background from non-qe events. The expected precision of the oscillation parameters are 1% for $\sin^2 2\theta_{23}$ and $\lesssim 10^{-4}$ eV^2 for Δm^2_{23}.

3.2. ν_e *appearance*

The signature of ν_e appearance in ν_μ beam is a single electromagnetic shower from ν_e CC interaction. Major sources of the background are beam ν_e contamination and ν_μ NC π^0 production. Combination of narrow spectrum and E_ν window cut greatly helps to reject both of the background, since the background show broad “reconstructed” E_ν distribution while that for the signal concentrates around the original peak of the ν_μ spectrum.

In the JHF-Kamioka project, a dedicated analysis algorithm is developed to reject the π^0 background as much as possible [8]. The expected reconstructed E_ν distribution after 5 years of exposure is shown in Fig. 5. The oscillation parameters of $\Delta m^2 = 3\times10^{-3}$ eV^2 and $\sin^2 2\theta_{13} = 0.1$ are assumed. A clear appearance peak is seen at the oscillation maximum of E_ν ~0.75 GeV. Also shown in Fig. 5 is 90%C.L. contours for 5 year exposure assuming 10% systematic uncertainty in background subtraction. The sensitivity of $\sin^2 2\theta_{13} = 0.006$ at 90% confidence level can be achieved in five years of operation. If $\sin^2 2\theta_{13}$ is larger than 0.018, then discovery of ν_e appearance is possible with the significance greater than 3σ.

3.3. CP violation and matter effect

All the future superbeam experiments aim to search for CP violation in the neutrino sector. In the experiments, difference of the probabilities between $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ will be searched for. In Fig. 6, relevant oscillation probabilities are plotted. As shown in the figure, the CP asymmetry can be as large as 40% even at

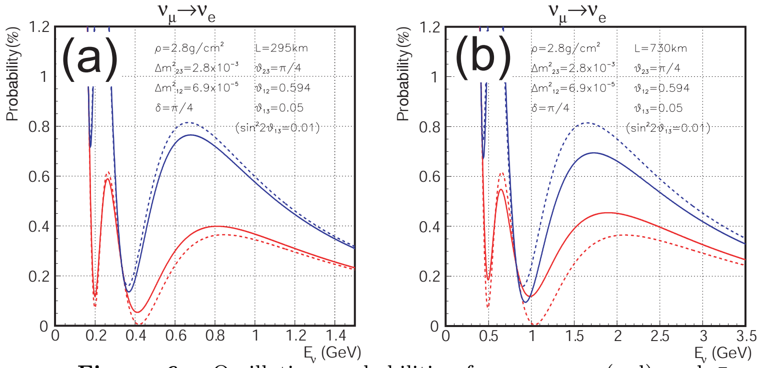

Figure 6. Oscillation probabilities for $\nu_\mu \to \nu_e$(red) and $\bar{\nu}_\mu \to \bar{\nu}_e$(blue) for baseline length of (a) 295 km and (b) 730 km. The solid curves includes asymmetry due to matter effect. For the dashed curves, the matter effect is subtracted and the difference between $\nu_\mu \to \nu_e$(red) and $\bar{\nu}_\mu \to \bar{\nu}_e$(blue) are all due to CP effect.

$\delta = \pi/4$. Matter effect also produces the difference and mimics the CP violation effect. The size the matter effect increases linearly with neutrino energy. Therefore, in order to be sensitive only on pure CP violation, the lower energy is better. In Fig. 6, the size of the matter effect is also drawn. At 1st oscillation maximum in 295 km case, the size of the matter effect is much smaller than the CP violation effect, but in the case of 730 km, those sizes becomes comparable. This, in turn, means that, at higher energies, there would be a chance to decide the sign of Δm^2 through the matter effect by combining with the lower energy measurements. The expected sensitivity on CP violation in 2nd phase JHF-Kamioka project is plotted in Fig. 7. If θ_{13} is of the order of 0.01 or larger, the CP violation phase δ can be explored down to $\sim 20°$.

4. Summary

The main goals of the next generation LBL experiments are discovery of ν_e appearance, precision measurements of oscillation parameters, search for CP violation. For those purposes, high statistics LBL experiments with conventional beam produced by MW-class proton accelerators, the *superbeam* experiments, are proposed in Japan, US and Europe. One or two order of magnitudes improvement in sensitivity is expected. The last unknown mixing $\sin^2 2\theta_{13}$ can be probed down to 0.006 and the expected precision of the parameters $\sin^2 2\theta_{23}$ and Δm_{23} are 1% and $\lesssim 10^{-4}$ eV^2 level, respectively. The CP violation can be searched for down to $\delta \sim 20°$. Start of the first superbeam experiment, possibly JHF-Kamioka project or OA-NuMI is very likely to be before 2010, much earlier than a neutrino factory. The exciting period of the field of neutrino physics will continue for coming decades.

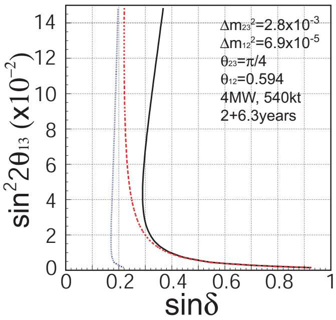

Figure 7. Expected 3σ discovery regions of $\sin\delta$ as a function of $\sin^2 2\theta_{13}$ after 2 (ν_μ) and 6.3 ($\bar{\nu}_\mu$) years of exposure in the phase II of JHF-Kamioka project. The (blue) dotted curve is the case of no background and only statistical error of signal, (red) dashed one is 2% error for the background subtraction, and (black) solid curve is the case that systematic errors of both background subtraction and signal detection are 2%. The values of other parameters are shown in the plot.

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5. Acknowledgments

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