FUTURE LONG-BASELINE PROGRAM*

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We review missing pieces of information about neutrinos and discuss methods of their measurements using oscillation experiments. We focus on the experiments using accelerator neutrinos and large detectors hundreds of kilometers away. Several projects based on powerful conventional beams of neutrinos are prepared for the next decade. We describe two most promising of them, which are T2K in Japan and NOνA in North America.

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1. Introduction

Ten years ago, in 1996, the Super-Kamiokande (SK) detector [1] was commissioned and started to collect data. Since then neutrino studies have revolutionized our ideas about leptons in the Standard Model of elementary particles. The neutrino oscillation, implying neutrino masses, was first discovered through a direction dependent deficit of muon atmospheric neutrinos [2]. The oscillatory character of this deficit has been later revealed in the SK data [3]. The neutrino mixing $\nu_\mu \leftrightarrow \nu_\tau$ explaining the atmospheric observations was recently confirmed by two long-baseline accelerator experiments. First the K2K Collaboration observed ν_μ disappearance using the neutrino beam from KEK and SK detector 250 km away [4]. Recently MINOS Collaboration published its first results [5,6], obtained using NuMI beam at Fermilab and Soudan detector 730 km away in Minnesota. They observed the ν_μ disappearance also consistent with the SK data.

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A deficit of solar neutrinos has puzzled physicists since the first results of the Homestake chlorine experiment (see the review in Ref. [7]). Missing electron neutrinos arriving from the Sun were later reported by other radio-chemical experiments using gallium nuclei. The mystery of solar neutrinos was deepened by the SK experiment, which was the first to prove that the neutrino events point to the Sun direction [8] and was able to measure energy and temporal distributions of the neutrino flux [9,10]. No modifications of the Standard Solar Model [11] were able to explain the results and the oscillation hypothesis was widely accepted as the viable solution of the solar neutrino puzzle. However, the final proof of the oscillation of electron neutrinos into a combination of muon and tau neutrino states, $\nu_e \leftrightarrow \nu_{\mu\tau}$, was provided by the SNO experiment [12–14]. It was able to measure separately the ν_e flux via CC reactions as well as the total flux of all flavors detecting neutrons from the NC deuterium disintegration. All solar observations are consistent with the scenario, in which ^{8}B electron neutrinos convert into a mass eigenstate by resonant matter effects inside the Sun [15]. This almost pure eigenmass state arrives then to Earth, where it can be modified by Earth matter effects.

The oscillation parameters which provide the explanation for solar neutrino data can be probed by reactor antineutrinos in a detector at sufficiently large distance. The measurements by KamLAND Collaboration found the evidence for $\overline{\nu_e}$ disappearance with the parameters consistent with the solar results [16] (assuming CPT invariance). Recent KamLAND data have also revealed oscillatory pattern [17].

The exciting search for solutions of the neutrino puzzles has thus been completed and we now have the firm evidence for neutrino oscillations. Still several of the oscillation parameters are either not well measured or not known at all. The next goal is to complete our understanding of neutrino mixing, to determine the ordering of the neutrino mass spectrum and to search for CP violation among neutrinos.

In this report we will describe some measurements which are planned for the next decade using accelerator neutrino beams.

2. Oscillation parameters and probabilities

In addition to the atmospheric and solar neutrino oscillations the LSND experiment observed a hint for oscillations [18]. This result is now checked by MiniBooNE experiment at Fermilab [19, 20]. The LSND observation would imply an existence of a fourth neutrino mass state. While waiting for MiniBooNE results we assume only 3-neutrino scenario. Let us only note that a global fit performed by Maltoni *et al.* in Ref. [21] of all atmospheric, solar, accelerator and reactor data was inconsistent with assumed scenarios of 4 mass states.

The three neutrino flavor eigenstates ν_α can be treated as a combination of three mass eigenstates ν_i using a 3×3 unitary mixing matrix U:

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i \,. \tag{1}$$

Consequently the neutrino mixing can be described by six real parameters: two independent differences of mass squared $\Delta m^2{}_{ij}$ (Δm^2_{12}, Δm^2_{23}), three mixing angles (θ_{12}, θ_{23}, θ_{13}), and a Dirac CP-violating phase δ. Two Majorana phases are omitted here because they do not show up in oscillations [22] (they affect only processes violating total lepton number)[1].

Using the PDG parametrization [23] the mixing matrix U of Eq. 1 can be written as a product of three rotations, each described by one of the mixing angles:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} , \tag{2}$$

where "s_{ij}" and "c_{ij}" stand for $\sin\theta_{ij}$ and $\cos\theta_{ij}$ respectively.

The last matrix describes solar neutrino mixing; the first matrix describes atmospheric neutrino mixing and the angle θ_{13} is known to be small (see below).

The probabilities of neutrino oscillations can then be given by (see *e.g.* Ref. [25]):

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} \; -4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right)$$

$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}) \sin\left(\frac{1.27\Delta m^2_{ij}L}{E}\right), \tag{3}$$

where L is a distance from the neutrino source to a detector in km while E stands for the neutrino energy in GeV for Δm^2_{ij} values given in eV^2. Note here that δ phase can only be measured when imaginary terms do not vanish. Consequently disappearance experiments, with $\alpha = \beta$ cannot measure the CP phase. Let us also note that for a complex matrix U, $P(\overline{\nu_\alpha} \to \overline{\nu_\beta}; U) = P(\nu_\alpha \to \nu_\beta; U^*)$.

It is seen from the formula that sensitivity to the oscillations with a given $\Delta m^2_{ij} \equiv |m_i^2 - m_j^2|$ is determined by the L/E value characteristic for

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[1] For a possibility to determine Majorana phases with neutrinoless double beta decays see Ref. [24].

an experiment. In a case when two independent Δm^2 values differ by orders of magnitude, $e.g.$ $|\Delta m_{23}^2| \gg |\Delta m_{12}^2|$ the formulae for probabilities can be simplified and only the terms for one Δm_{ij}^2 scale are left. The experiments have shown that we deal with such conditions as the difference of mass squared for atmospheric neutrinos is much larger than for solar neutrinos. Let us introduce notations: $\delta m^2 \equiv \Delta m_{12}^2$ and $\Delta m^2 \equiv \Delta m_{23}^2$. We therefore discuss experiments of an "atmospheric Δm^2 dominance" with small L/E values when the terms with δm^2 are very small and experiments of a "solar δm^2 dominance" with large L/E values when the terms with Δm^2 oscillate so fast that they can be averaged out to a constant.

For $\delta = 0$ we thus have the following survival probabilities in vacuum valid for "atmospheric domain" experiments:

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right), \tag{4}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right), \tag{5}$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right), \tag{6}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e) - P(\nu_\mu \to \nu_\tau). \tag{7}$$

For experiments in the "solar domain" one gets:

$$P(\nu_e \to \nu_{\mu\tau}) = \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{1.27 \delta m^2 L}{E} \right) - 0.5 \sin^2 2\theta_{13}. \tag{8}$$

In the limit of zero θ_{13}, these equations reduce even further to so called two-flavor oscillation formulae.

Following Ref. [15] we know that for neutrinos traversing the Earth the oscillation probability formula has to take into account matter (also called MSW) effect. This effect originates from the fact that different processes are possible for ν_e and $\nu_{\mu\tau}$ neutrinos scattering on electrons. As coherent forward scattering can be involved, the effect can be large. It gives rise of an extra interaction potential acting on electron (anti)neutrinos:

$$V = \pm\sqrt{2} G_{\rm F} N_e, \tag{9}$$

where $G_{\rm F}$ is the Fermi coupling constant, N_e is the number of electrons per unit volume and the positive sign corresponds to ν_e while negative to $\overline{\nu_e}$. As a result a two-flavor oscillation formula can be written as:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_M \sin^2 \left(\frac{1.27 \Delta m_M^2 L}{E} \right), \tag{10}$$

where

$$\Delta m_M^2 \equiv \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}\,, \tag{11}$$

$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \tag{12}$$

and $x = \frac{2VE}{\Delta m^2}$.

3. What is known about the oscillation parameters

As noted in previous section the oscillation probabilities given by (3) can be approximately measured either in the "atmospheric domain" when L/E is smaller than around 1000 km/GeV or "solar domain" in experiments with much larger L/E. In this approximation the mixing angles θ_{23} and θ_{12} are left only in "atmospheric" or "solar" formulae respectively, while the θ_{13} angle remains in both.

3.1. Experiments with the "atmospheric Δm^2 dominance"

The first evidence for the neutrino oscillations has been derived from the observation of the muon neutrino disappearance in SK detector as a function of the neutrino flight length [2]. Because the electron neutrinos were observed as expected it was deduced from formulae (4) and (5) that θ_{13} has to be small and the disappearance is due to dominant transition $\nu_\mu \leftrightarrow \nu_\tau$. Soon afterwards the CHOOZ experiment [27] published a negative result on a search for reactor $\overline{\nu}_e$ disappearance and thus set the most stringent upper limit on θ_{13} (see below).

In the standard oscillation analysis the two-flavor approximation of the formula (7) (assuming $\theta_{13} = 0$) was fitted to the zenith angle distributions in several energy intervals. The Super-Kamiokande data (SK-I) from the first phase of the detector activity from April 1996 to July 2001 have been published in Ref. [26] on the basis of the sample of 15350 data events.

A somewhat more accurate measurement of Δm^2 was obtained using a subsample of 2726 events with a good resolution in the flight length L, which was derived from the reconstructed neutrino direction. The analysis allowed to reveal a dip in the distribution of L/E.

The results of two-flavor fit of the $\nu_\mu \leftrightarrow \nu_\tau$ transitions to both data samples are summarized in Table I.

The SK data also show some supporting evidence that muon neutrinos are transformed primarily into τ neutrinos [28]. Studies have however ruled-out any significant mixing with a hypothetical sterile neutrino [29, 30].

TABLE I

Oscillation parameters from two-flavor disappearance fits to the Super-Kamiokande (SK) and K2K data. The fits to SK angular distributions come from Ref. [26], while the results of L/E analysis from Ref. [3]

Experiment	Best fit		Limits at 90% c.l.	
	$\|\Delta m^2\|$ $[\times 10^{-3}\ \mathrm{eV}^2]$	$\sin^2 2\theta_{23}$	$\|\Delta m^2\|$ $[\times 10^{-3}\ \mathrm{eV}^2]$	$\sin^2 2\theta_{23}$
SK-I (ang. distr.)	2.1	1.0	1.5–3.4	> 0.92
SK-I (L/E)	2.4	1.0	1.9–3.0	> 0.90
K2K	2.8	1.0	1.9–3.6	

After the discovery of the atmospheric neutrino oscillations an independent check using a controlled accelerator beam became essential. An obvious option was to take advantage of the world's largest neutrino detector, SK, and the KEK accelerator at a distance of 250 km. This led to the K2K (KEK to Kamioka) experiment [31] using the neutrinos of a mean energy of 1.3 GeV. On the basis of the data corresponding to 0.89×10^{20} protons on target (POT) the Collaboration published evidence for ν_μ disappearance in Ref. [4]. In total 107 events of ν_μ interactions were observed in SK while 151^{+12}_{-10} would be expected without oscillations. This deficit as well as the neutrino spectrum modulation are best described by oscillation parameters given in Table I. The same results have been obtained from the preliminary analysis of the complete K2K data set corresponding to 1.05×10^{20} POT [32].

Recently the MINOS Collaboration announced its first oscillation results [5]. After 0.93×10^{20} POT exposure to the NuMI beam (with the peak energy around 3.5 GeV) they have found 92 muon neutrino events in the Soudan detector 730 km away, while 177 ± 11 muon neutrinos were expected without oscillations. The observation is consistent with the following oscillation parameters: $\Delta m^2_{23} = (3.05^{+0.60}_{-0.55}(\mathrm{stat}) \pm 0.12(\mathrm{syst})) \times 10^{-3}\ \mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(\mathrm{stat}) \pm 0.06(\mathrm{syst})$. The result is then consistent with SK atmospheric and K2K accelerator neutrino results.

In summary the current results of the "atmospheric Δm^2 dominance" experiments tell us that at least one of the neutrino masses is larger than 44 meV. The best estimates point to a maximal mixing angle $\theta_{23} = 45°$.

3.2. Experiments with the "solar δm^2 dominance"

The precision measurements of ^{8}B solar neutrinos come from the SNO and SK experiments [14, 33]. The SNO heavy-water detector is able to measure separately the CC interactions on neutron (for ν_e only), the NC interactions on nucleons (for sum of all the flavors) and combined CC/NC scattering on electrons. On the other hand SK has a very large sample of scatterings on electrons with energies above 5 MeV. The energy spectrum of recoiling electrons provides a strong constraint on the oscillation analysis. The analyses have shown that the ν_e oscillation is dominated by matter effects in the Sun.

KamLAND uses electron antineutrinos from distant reactors up to 200 km away. It was able to observe an oscillatory behavior of the measured event rate as a function of L/E [17] and obtained the most precise determination of $\delta m^2 = (7.9^{+0.6}_{-0.5}) \times 10^{-5}$ eV^2. When the latest results from solar and reactor experiments are compared under the assumption of fundamental CPT invariance the best fit parameters of $\nu_e \leftrightarrow \nu_{\mu\tau}$ transitions are $\delta m^2 = (8.0^{+0.6}_{-0.4}) \times 10^{-5}$ eV^2 and $\theta = 33.9^{+2.4}_{-2.2}$ degrees (Ref. [14]). The mixing angle is thus significantly different from maximal.

3.3. Upper limits on θ_{13}

The most restrictive limits on θ_{13} have been obtained by the CHOOZ reactor experiment [27] which searched for $\overline{\nu_e}$ disappearnce. It used a detector with Gd-loaded scintillator for efficient neutron detection about 1 km away from the reactor (100 km/GeV $< L/E <$ 500 km/GeV). CHOOZ established an upper limit on the disappearance probabilities in function of Δm^2. Knowing from atmospheric neutrino measurements that θ_{13} is small the upper bounds on θ_{13} could be determined using formula (4).

The bounds are shown in Fig. 1, taken from a paper by Maltoni *et al.* [21]. The authors performed global fits to all existing data with the assumption of one mass scale dominance ($\delta m^2 = 0$). They also noted that adding KamLAND data to the fits in the atmospheric domain has a surprisingly strong impact on this bound at smaller values of Δm^2, where large L/E values improve the sensitivity. For $\Delta m^2 = 2.4 \times 10^{-3}$ eV^2 they find $\sin^2\theta_{13} < 0.022$ at 90% c.l. and $\sin^2\theta_{13} < 0.051$ at 3σ.

Recently a three-flavor oscillation analysis has been published [34] using SK-I atmospheric neutrino data also assuming one mass scale dominance ($\delta m^2 = 0$). A sensitivity to θ_{13} is due to matter effect, which occurs when neutrinos propagate inside the Earth. The $\nu_\mu \rightarrow \nu_e$ transition probability may become large at $5 \sim 10$ GeV neutrino energy for not too small θ_{13} values. As no significant effect has been observed a constraint on θ_{13} has been set. The best-fit for three-flavor oscillation was obtained
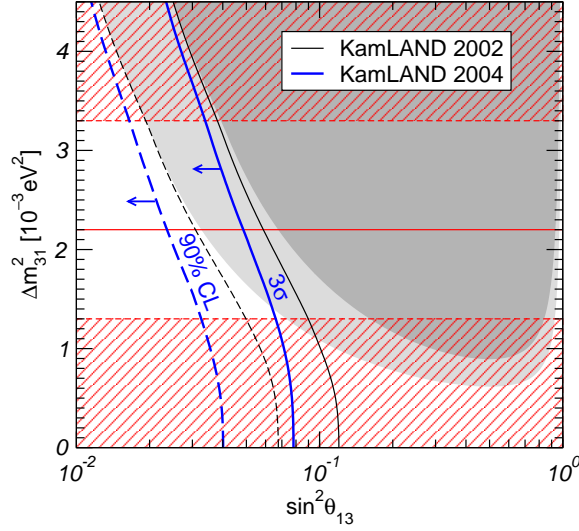
Fig. 1. Upper bound on $\sin^2\theta_{13}$ from solar+KamLAND+CHOOZ data as a function of Δm^2. The dashed (solid) curve corresponds to the 90% (3σ) c.l. bound, the thin curves have been obtained with 2002 KamLAND data, whereas the thick curves follow from the 2004 KamLAND update. The light (dark) shaded region is excluded by CHOOZ data alone at 90% (3σ) c.l. The horizontal line corresponds to the best fit value of Δm^2 from atmospheric + K2K data, and the hatched regions are excluded by atmospheric + K2K data. From Maltoni *et al.* [21].

at $(\Delta m^2, \sin^2\theta_{23}, \sin^2\theta_{13}) = (2.5 \times 10^{-3}\mathrm{eV}^2, 0.5, 0.0)$ and the upper limits were set at $\sin^2\theta_{13} < 0.14$ and $0.37 < \sin^2\theta_{23} < 0.65$ at 90% c.l. assuming normal hierarchy. A wider region is allowed in the inverted hierarchy case.

On top of the ν_μ disappearance analysis a search for ν_e appearance has been performed by K2K Collaboration [35–37]. A single electron candidate has been found, consistent with background expectation coming mostly from neutral current π^0 production by ν_μ. This allows to exclude at 90% c.l. $\nu_\mu \leftrightarrow \nu_e$ appearance with parameters: $\sin^2 2\theta_{\mu e} > 0.13$ at $\Delta m^2 = 2.8 \times 10^{-3}\mathrm{eV}^2$, the best fit value of the K2K ν_μ disappearance analysis. The upper bound on $\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13} \sin^2\theta_{23}$ can be translated into $\sin^2 2\theta_{13} > 0.26$ for $\sin^2\theta_{23} = \frac{1}{2}$.

4. What remains to be measured and the problem of degeneracies

We list here the most important observations and measurements which can be made using neutrino oscillations.

4.1. Observation of ν_τ appearance

Even though all the existing data are consistent with the dominant $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the "atmospheric domain", no significant signal of τ appearance has been found. The K2K and MINOS long-baseline experiments were designed for a good sensitivity at the first oscillation maximum and so the neutrino energies were too small to observe τ leptons from CC interactions of ν_τ. This task has been taken by OPERA Collaboration which uses CNGS beam (from CERN to Gran Sasso) with average neutrino energies of about 18 GeV and the detector with emulsion foils for an optimal space resolution to identify τ lepton decays [38].

Also, as noted above, SK atmospheric neutrino data indicate an excess of τ-like events among the sample of upward-going neutrinos interacting inside the detector.

4.2. Hierarchy of neutrino mass states

The current experimental data do not tell us what are the absolute values of neutrino masses; the laboratory limits from measurements of tritium decay spectra are as high as 2.2 eV. Moreover, the differences of the mass squared, which have been measured, can be ordered in two different ways as is illustrated in Fig. 2. The mass of the lightest neutrino is assumed to be zero for the illustration. The two possible mass ordering are referred to as "normal" or "inverted" hierarchy.

To solve the hierarchy problem we need to measure the sign of $\Delta m_{23}^2 \equiv m_2^2 - m_3^2$. The most promising way is offered by the matter MSW effects because the sign enters the formulae (11) and (12) for effective matter parameters Δm_M^2 and $\sin^2 2\theta_M$. An experiment can either compare the matter effects for neutrinos and antineutrinos or look for modifications of neutrino spectra after long path-lengths. The matter effects come from differences in scattering on electrons experienced by electron and other flavor neutrinos and therefore are observable only for non-zero θ_{13}. The size of the effect is determined by a ratio $x = \frac{2VE}{\Delta m^2}$ and so it grows with neutrino energy.

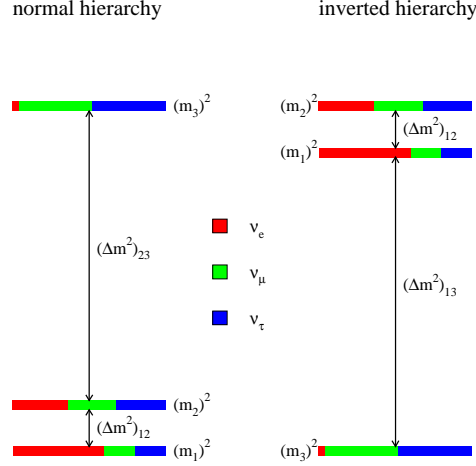normal hierarchy   inverted hierarchy

Fig. 2. The two possible arrangements of the masses of the three known neutrinos. On the left is a "normal hierarchy", and on the right an "inverted" one. The color shading indicates the fraction $|U_{\alpha i}|^2$ of each distinct flavor ν_α, $\alpha = e, \mu, \tau$, contained in each mass eigenstate ν_i, $i = 1, 2, 3$. From Ref. [39].

4.3. Mixing angle θ_{13}

A very important goal of the future experiments is the determination of the small parameter θ_{13}. A non-zero value for θ_{13} is necessary to probe both the CP violation phase δ as well as to resolve the ordering of neutrino mass states. To search for an order of magnitude improvement over a current limit of $\sin^2 2\theta_{13} < 0.1$ experimental sensitivities to a signal of 1% are needed.

It is seen from Fig. 2 that in order to measure θ_{13} one should probe a small component of ν_e in one of the atmospheric doublet states. Therefore, one needs an experiment with a distance to energy ratio L/E characteristic to atmospheric oscillation frequency *i.e.* around 500 km/GeV. It should also involve electron neutrinos. Consequently there are 2 types of experiments using reactor and accelerator beams.

4.3.1. Reactor $\overline{\nu_e} \rightarrow \overline{\nu_e}$ disappearance

With $\overline{\nu_e}$ energies of a few MeV the optimal distance is around 1 km. The transition probability is given by the simple formula (4) because the matter effects are insignificant at that energy and neutrino path length. Also CP violation terms vanish as required for a disappearance experiment. It then follows that reactor experiments offer the "cleanest" way of the θ_{13} determination.

A successor of CHOOZ will be the Double-CHOOZ experiment [41], planned to start in 2008 with two detectors, with a goal to reduce systematic errors down to 0.6% and to reach a sensitivity on $\sin^2 2\theta_{13} \simeq 0.024$ (90% c.l., $\Delta m^2 = 2.5 \times 10^{-3}$) in a 3 year run.

4.3.2. Accelerator $\nu_\mu \rightarrow \nu_e$ appearance

In a $\nu_\mu \rightarrow \nu_e$ experiment neutrino energy and a distance to a detector have to be optimized keeping L/E close to the first oscillation maxima and taking into account cross-sections rising with energies, while the flux falling with the distance. It follows that the optimal energies are around a few GeV's and neutrino travel distances of hundreds of km.

In general a probability for the $\nu_\mu \rightarrow \nu_e$ transition involves terms with CP phase δ and matter effects have to be taken into account for precision measurements with that large distances. The $\nu_\mu \rightarrow \nu_e$ transition probability is given by the complicated formula [42]:

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) &= 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{13} \\
&+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \Delta_{23} \sin \Delta_{13} \sin \Delta_{12} \\
&- 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin \delta \sin \Delta_{23} \sin \Delta_{13} \sin \Delta_{12} \qquad \text{(CPV)}, \\
&+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta\} \sin^2 \Delta_{12} \quad \text{(solar)}, \\
&- 8c_{12}^2 s_{13}^2 s_{23}^2 0.5 |V| L (1 - 2s_{13}^2) \cos \Delta_{23} \sin \Delta_{13} \qquad \text{(matter)},
\end{aligned}
$$
$$(13)$$

where $\Delta_{ij} \equiv \frac{1.27 \Delta m_{ij}^2 L}{E}$ and the matter effects (with potential V given by (9)) are only given at the first order[2]. The first term is dominant for not too small θ_{13}. The third term contains $\sin \delta$ and thus is CP violating. At distances of only hundreds of km the forth ("solar") term will generally be small, however for very small θ_{13} this is the only non-vanishing term. For antineutrinos the third and the last term will change sign giving rise to one of the possible degeneracies when matter effects can mimic the "true" CP-violating effects.

4.4. Octant of the mixing angle θ_{23}

One of basic questions to answer is whether θ_{23} is exactly equal to $\pi/4$ suggesting an unknown symmetry. The lower bound found for $\sin^2 2\theta_{23} > 0.9$ implies a range of $37°$–$53°$ for θ_{23}. In order to determine the octant one needs to measure $\sin^2 \theta_{23}$ and not only $\sin^2 2\theta_{23}$ as in the dominant term of the ν_μ disappearance. As mentioned above the first bounds on $\sin^2 \theta_{23}$ have

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[2] See *e.g.* Ref. [50] for a more complete treatment of matter effects.

been obtained from the 3-flavor analysis of the SK-I atmospheric data. Much more accurate measurements are needed to measure subdominant terms containing $\sin^2 \theta_{23}$; possibly only neutrino factories will be able to resolve the $\theta_{23}, \pi/2 - \theta_{23}$ ambiguity.

4.5. CP violation

For fundamental reasons we need appearance experiments to search for CP violation effects. Essentially, in order to study a CP symmetry in neutrinos one should compare transition probability $P(\nu_\alpha \to \nu_\beta)$ with a probability for its CP-mirror image $P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$. Any difference between two probabilities would mean a violation of CP invariance.

In the parametrization given by (2) the CP-violating phase δ enters the mixing matrix U only in combination with $\sin \theta_{13}$ and so the CP-violating difference $P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu_\alpha} \to \overline{\nu_\beta})$ will depend on θ_{13}. As explained in Ref. [25] the parametrization has been chosen because the CP-violating effects disappear if any of the mixing angle is zero. Thus δ can be measured only if $\theta_{13} > 0$.

The asymmetry measuring a difference in neutrino and antineutrino appearance probabilities is for not too small θ_{13} given by:

$$A = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})} \simeq \frac{\Delta m_{12}^2 \, L}{4 \, E_\nu} \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \, \delta \,. \tag{14}$$

The effect of the CP violation is thus proportional to $1/\sin \theta_{13}$ while $P(\nu_\mu \to \nu_e)$ is proportional to $\sin^2 2\theta_{13}$. For large values of θ_{13}, A will be small even if characterized by large number of oscillated events. Hence systematic uncertainties would dominate. For small values of θ_{13} a possible signal will be limited by event statistics and background rates.

A difference between neutrino and antineutrino oscillations can be caused not only by the "true CP violation" but also by matter effects. This causes ambiguities in extracting δ and $\mathrm{sign}(\Delta m_{23}^2)$ from experimental data. At baselines of ~ 100 km these effects are negligible while at ~ 700 km they can be up to $\sim 30\%$ of the probabilities in vacuum [40].

4.6. Degeneracies

Matter effects can mimic CP-violation in vacuum. The ambiguities coming from absence of information about the mass hierarchy and matter effects faking the true CP-violation can be additionally complicated by correlations between θ_{13} and δ and the unknown octant of θ_{23}. Barger et al. [43] noticed that the three-neutrino analysis of long-baseline experiments can lead to an eight-fold degeneracy in the oscillation parameters because measurements

of $P(\nu_\mu \to \nu_e)$ and $P(\overline{\nu_\mu} \to \overline{\nu_e})$ may result in eight allowed regions of the parameter space,

In order to lift the degeneracies multiple detectors are needed for studies of $\nu_\mu \to \nu_e$ appearance or multiple experiments. Specific solutions involve using the same beam and 2 far detectors: Tokai to Korea and Super-NOνA projects; they will be described briefly in Sec. 7.

Another idea has been suggested in Ref. [44]. As data from atmospheric neutrinos are in principle sensitive to the θ_{23} octant and to the type of the neutrino mass hierarchy combining the Hyper-Kamiokande data with T2K (phase II) results can help to resolve the degeneracies.

5. Neutrino beams

Neutrinos in the next decade will come from conventional beams *i.e.* ν_μ's from meson decays produced by intense beams of protons. Beams with (proton) power above 0.5 MW are sometimes called Super Beams.

Important conditions for the experiments are: ν_μ beam of high intensity, a small contamination by ν_e and $\overline{\nu_\mu}$ and narrow band neutrino spectrum. Detectors should provide a good identification of ν_e interactions (*i.e.* secondary electrons) for efficient reduction of π^0 background.

Two neutrino beams are now in operation at Fermilab [45]. The Booster beam uses 8 GeV protons with secondary mesons decaying in a 50 m decay region. An average neutrino energy is approximately 600 MeV. After a few year exposure of Mini-BooNE detector to ν_μ beam, the magnetic horns are currently set to form $\overline{\nu_\mu}$ beam. The NuMI beam uses 120 GeV protons extracted from the Main Injector and 675 m decay pipe. The neutrino energy can be set by changing the target position with respect to the focusing horns. The peak event rate can be at neutrino energies: 3.5 GeV ("low") or higher. It is designed for 4×10^{13} protons per pulse (PPP). Since January 2005 it has provided ν_μ's for MINOS experiment [6].

Both K2K and MINOS detectors were positioned along the neutrino beam axis. Future experiments are however designed for off-axis beams. The advantage of the off-axis beam is a smaller spread of neutrino energies and smaller contamination with ν_e. With much reduced tail of higher energies the background coming from NC interactions is much smaller. The advantage of using a beam at an angle θ from an axis of focused pions comes from pion decay kinematics. Energies of neutrinos, $E_\nu = 0.43E_\pi/(1 + \gamma^2\theta^2)$, emitted at a given angle θ different from zero are much less dependent on original pion energy E_π.

Using NuMi "medium" energy beam at an angle of 14 mrad the spectrum will peak around 2 GeV with a FWHM of 800 MeV [45] and will have little background from a contamination of ν_e from K decays. It is expected that an improved NuMi beam will achieve a rate of 6.5×10^{20} POT annually (without a Proton Driver which would enhance the flux by a factor of 5).

In Japan a powerful ν_μ beam is currently being built in Tokai, at J-PARC (Japan Proton Accelerator Research Complex) laboratory [46]. The beam design aims at 0.75 MW power for 40 GeV protons. The ν_μ beam intensity is two orders of magnitude larger than that of K2K. At the peak energy the ν_e contamination is estimated at 0.4%. For the second phase an upgrade of linac and main ring is planned which would allow to achieve a power of 4 MW. With 2–3 degrees off axis the beam will cover both SK and a site chosen for Hyper-Kamiokande (see below).

6. Current and future long-baseline experiments

MINOS is the first experiment to use NuMi beam. The neutrino interactions are recorded in a 980 ton near detector 1 km away and a 5.4 kton far detector at 730 km. Both detectors contain magnetized iron slabs and scintillator sampling calorimeter. The first published results corresponded to about 1×10^{20} POT. MINOS Collaboration hopes to achieve 25×10^{20} POT in 5 years. Its goal is to determine $|\Delta m_{23}^2|$ with 10% accuracy and improve the CHOOZ θ_{13} limits by a factor of 2; the sensitivity will be determined by statistical fluctuation of the π^0 background.

Two experiments in advanced stages of preparation (or planning) are T2K (Tokai to Kamioka) and NOνA (see Table II).

TABLE II

Basic specifications of T2K and Nova experiments (1st phases).

	T2K	NOνA
Accelerator	J-PARC at Tokai	Main Injector at Fermilab
Beam status	being constructed	NuMI (upgraded)
Proton energy	40 GeV	120 GeV
Neutrino energy (peak)	0.76 GeV	2.22 GeV
Far detector	Super-Kamiokande	to be built
Total mass	50 kton	30 kton
Fiducial volume mass	22.5 kton	
Distance	295 km	812 km

7. T2K experiment

T2K (Tokai to Kamioka) experiment will use J-PARC beam 2.5° off axis and the Super-Kamiokande detector 295 km away [47, 48]. SK detector has just been rebuilt after the accident in 2001 and its photocathode coverage brought back to the original 40% with about 12000 PMTs. To control the beam, muon monitors will be located 140 m downstream from the target. The first front detector will be at 280 m and later a second detector is planned along the off-axis beam, 2km from the target. The data taking is planned to start in April 2009.

The T2K Collaboration will profit from the experience gained while running the K2K experiment. Also the SK detector feasibility, in particular for selection of ν_e interactions from the background, is well explored and understood.

7.1. Phase I

The sensitivity to θ_{13} depends on a value of CP violating phase δ. Assuming $\delta = 0$ the sensitivity for $\sin^2 2\theta_{13} > 0.008$ is expected after an exposure to 5×10^{21} POT. It's hoped that this exposure will be obtained in 5 years. For the worst case of $\delta = 90°$ the significant signal for $\sin^2 2\theta_{13} > 0.02$ may be expected. Also the precision $\delta(\sin^2 2\theta_{23}) \sim 0.01$ and $\delta(\Delta m_{23}^2) \sim 1 \times 10^{-4}$ should be achieved.

Due to relatively short distance of 295 km T2K (phase I) will not be sensitive to mass state ordering. However its potential in θ_{13} determination may be unique as displayed in Fig. 3.

7.2. Phase II

If non-zero θ_{13} is established during the phase I of the experiment it is planned to upgrade the beam to 4 MW. Also a larger detector, Hyper-Kamiokande (HK), is designed to be located in a mine 8 km from the site of near SK and KamLAND. It will be a water Cherenkov, modular detector of fiducial volume of 0.54 Mton. Assuming 5-fold increase in the beam intensity the expected sensitivity to $\sin^2 2\theta_{13} > 0.003$ is estimated after next 5 years (again for $\delta = 0$).

With the present beam line configuration the J-PARC neutrino beam is aimed at Korea . The baseline length between J-PARC and Korea is more than 1000 km. Due to the large neutrino flight length in matter, a detector in Korea could be very useful for the determination of the neutrino mass hierarchy, allowing to lift two-fold CP phase ambiguity. Two possible detector locations are discussed; one is a nearest place to the J-PARC beam on-axis for detecting higher energy neutrinos, and the other near the 2.5
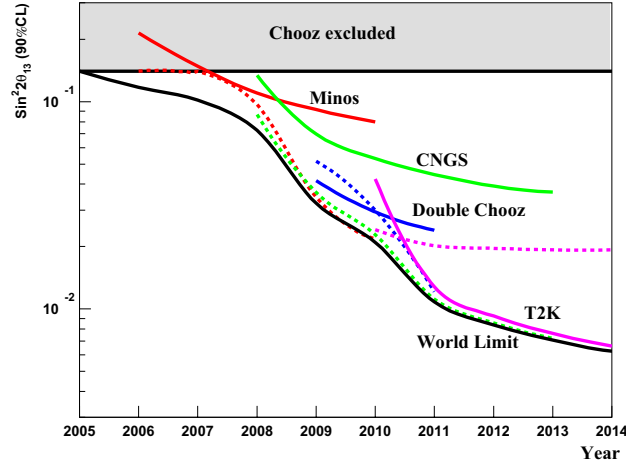
Fig. 3. Evolution of sensitivities on $\sin^2 2\theta_{13}$ with time. For each experiment its sensitivity (solid line) and the world sensitivity computed without the experiment (dashed line) are displayed. The comparison of the two curves shows the discovery potential of the experiment along its data taking. The world overall sensitivity along the time is also displayed. The comparison of the overall world sensitivity with the world sensitivity computed without a single experiment shows the impact of the results of the single experiment. Experiments are assumed to provide results after the first year of data taking. Taken from Ref. [40].

degree off-axis for detecting sub-GeV neutrinos. Plastic scintillator, water Cherenkov and liquid Argon detectors are discussed as possible installations in Korea.

Ishitsuka *et al.* [49] considered a possibility of simultaneous determination of neutrino mass hierarchy and the CP violating phase by using two identical water Cherenkov detectors, one placed in Kamioka and the other in Korea. They show that the two-detector complex with each fiducial volume of 0.27 Mton has potential of resolving neutrino mass hierarchy for $\sin^2 2\theta_{13} > 0.03$ (0.055) at 2σ (3σ) C.L. for any values of δ. An example illustrating how the degeneracy of the solutions can be resolved is shown in Fig. 4.

At the same time the proposed complex has the sensitivity to CP violation by $4 + 4$ years running of ν_e and $\bar{\nu}_e$ appearance measurement. The significantly enhanced sensitivity is due to clean detection of modulation of neutrino energy spectrum, which is enabled by cancellation of systematic uncertainties between two identical detectors which are exposed to the same neutrino beam.

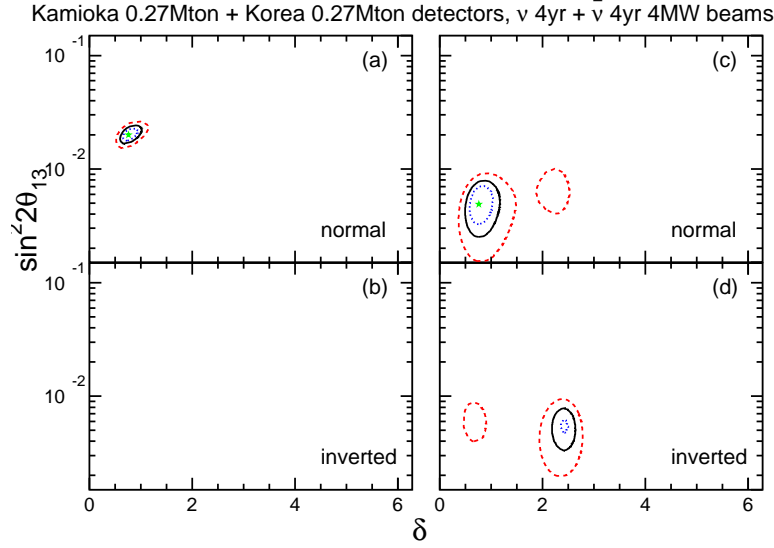Kamioka 0.27Mton + Korea 0.27Mton detectors, ν 4yr + ν̄ 4yr 4MW beams

Fig. 4. Examples of the parameter degeneracy for two detectors one in Kamioka and the other in Korea (twin HK). The true solutions are assumed to be located at $(\sin^2 2\theta_{13}$ and $\delta) = (0.02, \pi/4)$ (left panels) and $(0.005, \pi/4)$ (right panels) with positive sign of Δm^2_{31}, as indicated as (green) stars. Three contours in each figure correspond to the 68% (dotted lines, blue), 90% (solid lines, black) and 99% (dashed lines, red) C.L. sensitivities. The figure taken from [49].

8. NOνA experiment

The NOνA experiment is designed to use NuMI beam at 14 mrad off the axis. The far detector located 810 km from Fermilab will be constructed of approximately 24000 PVC extrusions of 15.7 m length, filled with liquid scintillator, arranged in alternating planes with horizontally and vertically arranged extrusions. The total detector mass will be 30 kton and length of 132 m. In each intrusion the scintillation light will be captured by a wavelength-shifting fiber read by 32 pixel avalanche photodiode [45]. The detector will be located on the surface, possibly with a few meter overburden.

Approximately 2000 ν_μ CC events are expected for each 7×10^{20} POT. The efficiency for saving ν_e interactions after cuts reducing π_0 background is expected at 24%.

The sensitivity to $\sin^2 2\theta_{13}$ is expected to get down to 0.02 for all δ values and to approximately 0.008 for some δ. Owing to higher energy and larger distance NOνA will have three-fold bigger matter effects and thus is expected to resolve the mass hierarchy problem for a large fraction of possible δ values.

In order to tackle the problem of degeneracies an interesting second-phase experiment is proposed under the name of Super-NOνA. Mena *et al.* [50–52] consider two detectors characterized by the same L/E ratios but at different baselines L and different off-axis angles leading to different neutrino spectra. The authors have found that with such a configuration vacuum oscillation phases are the same at both sites, enabling to extract matter effects and thus the type of mass hierarchy. They consider two large multi-kton liquid Ar TPC detectors with excellent electron resolution, probably based on commercial technology of large tank construction.

9. Summary

The masses and mixing of the neutrinos are suggested in extensions of the Standard Model as the low energy remnant of some yet unknown high energy physics. Thus, the studies of neutrino oscillations provide a unique window on physics that is inaccessible to collider experiments.

The neutrino oscillation program for the next decade has ambitious goals to answer a few basic questions. What is the ordering of the neutrino mass states? Is θ_{23} exactly equal to $\pi/4$ or $\theta_{13} = 0$ suggesting an unknown symmetry? Are the neutrino and antineutrino oscillations the same? An answer to the latter question is fundamental for leptogenesis and baryon asymmetry in the Universe. Understanding symmetries in lepton sector is also essential for unification theories.

In order to settle these problems the precision of the oscillation parameters, especially in the atmospheric domain, has to be improved. Determination of θ_{13} will be the critical issue for further studies, because its value is decisive for strategies how to measure CP phase and determine mass hierarchy.

Reactor experiments, insensitive to CP effects, will most probably provide first estimates of θ_{13} values or limits. However, they will not be able to measure δ_{CP}, sign(Δm_{23}^2) nor to improve accuracy on $|\Delta m_{23}^2|$ and $\sin^2 2\theta_{23}$. This will be the task of accelerator experiments using powerful neutrino beams. Resolving multiple degeneracies may be very challenging, requiring more than one experiments.

In summary the program for the future of long-baseline experiments seems well scheduled. Within next 4 years (until 2010) we can expect improved precision on the parameters Δm_{23}^2 and $\sin^2 2\theta_{23}$ with ν_μ disappearance studies by MINOS Collaboration. Atmospheric ν studies should also improve the accuracy of $\sin^2 2\theta_{23}$. Possibly at the end of this period we will see the $\nu_\mu \leftrightarrow \nu_\tau$ transitions confirmed with ν_τ appearance by OPERA.

The next era should significantly improve our knowledge of θ_{13} mixing. Around 2009 three experiments: Double-CHOOZ, T2K and NOνA should be commissioned. Until 2015 the θ_{13} mixing should be explored down to $2°$ and hopefully the $\nu_\mu \to \nu_e$ transitions will be observed. Further experimental schedule will then be settled on the basis of the size of θ_{13} mixing.

Combining the NOνA and T2K results will facilitate a separation of CP violation from matter effects. Interesting projects to use complexes of two large detectors in Japan and Korea or/and in North America (Super-NOνA) may be necessary to lift some degeneracies.

If Super Beams are not able to solve the problems, cleaner and more intense beams and larger detectors may be needed. Two approaches are now considered: beta beams and neutrino factories [54]. Beta beams offer pure ν_e or $\overline{\nu_e}$ beams from decays of accelerated ^{6}He or ^{18}Ne ions. Neutrino factories would provide *e.g.* 50% $\overline{\nu_\mu}$ and 50% ν_e from μ^+ decays with very small beam systematics, requiring however good lepton charge measurement.

In parallel with this rich program of long-baseline experiments the next decade should bring much improved results on neutrino-less double beta decays "$0\nu2\beta$, essential for revealing the very nature of neutrinos (Dirac or Majorana). Let us note here that there is an important synergy between the two fields of neutrino study. The "$0\nu2\beta$" experiments probe electron-rich mass states and thus a sensitivity to $\langle m \rangle \sim 50$ meV may be enough for a positive signal in case of inverted hierarchy. The normal hierarchy is much more difficult to probe and would imply a target mass 10 times larger (*e.g.* 1 ton instead of 100 kg).

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