

11: NEUTRINO MASSES AND OSCILLATIONS

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Abstract. New experimental results on neutrino masses and oscillations are reviewed. Notable result is the atmospheric neutrino data from Super-Kamiokande, which shows a strong distortion in angular distributions. The result gives a hint of neutrino oscillations. Other subjects are neutrino mass experiments, accelerator-based neutrino oscillation experiments, solar neutrinos and future neutrino experiments.

1 Introduction

Currently unresolved issues about neutrinos are masses and oscillations. If neutrinos have masses, it gives a strong clue for physics beyond the standard model. Furthermore, neutrinos may have played an important role in astrophysics through dark matter.

Direct searches for neutrino masses are performed by Tritium beta decay experiments for $\bar{\nu}_e$, $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay for ν_μ , and τ decay measurements for ν_τ . Double beta decay gives an information of Majorana neutrino masses.

Although neutrino oscillation experiments are sensitive to only mass differences of neutrino species, much smaller mass ranges can be investigated than direct search experiments. A probability of neutrino oscillations is given by the following formula:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left(1.27 \frac{L}{E} \Delta m^2 \right), \quad (1)$$

where θ is the mixing angle of neutrinos, L is the distance from a neutrino source to a detector in unit of kilometer, E is the energy of neutrinos in unit of GeV, and Δm^2 is the difference of mass squares in unit of eV^2 . As seen in the equation, one needs longer distance and smaller energy of neutrinos for investigating small Δm^2 . The neutrino oscillation experiments with a baseline of sun-to-earth or earth-size, namely solar neutrino and atmospheric neutrino experiments, are best suited for searching for small Δm^2 . To search for small mixing angle, one needs high statistics of neutrino events, which are available at accelerator-based experiments. The MSW mechanism^[1] of solar neutrino oscillations has given a tool to investigate small mixing angle for $\Delta m^2 = 10^{-7} - 10^{-4} \text{ eV}^2$ range.

In this report, recent results on neutrino masses and oscillation experiments are described.

2 Neutrino mass experiments

A finite mass of $\bar{\nu}_e$ should bend down the Tritium beta decay spectrum in the vicinity of the end-point. Results of Tritium experiments are summarized in Table 1. As seen in the table, all experiments give negative value of m_ν^2 . The

Experiment	m_ν^2	m_ν limit
INS Tokyo 91	$-65 \pm 85 \pm 65\text{eV}^2$	13.1 eV
LANL91	$-147 \pm 68 \pm 41\text{eV}^2$	9.3 eV
Zürich 92	$-24 \pm 48 \pm 61\text{eV}^2$	11.7 eV
China 93	$-31 \pm 75 \pm 48\text{eV}^2$	12.4 eV
Livermore 95	$-130 \pm 20 \pm 15\text{eV}^2$	7 eV
Mainz 94	$-22 \pm 17 \pm 14\text{eV}^2$	5.6 eV
Troitsk 94	$-22 \pm 4.8\text{eV}^2$	4.35 eV
Troitsk 94+96	$-1 \pm 6.3\text{eV}^2$	3.5 eV
PDG (96)	$-27 \pm 20\text{eV}^2$	

Table 1. Results of Tritium neutrino mass experiments.^[2] The fitted m_ν^2 and 95 % C.L. limits are shown. The results of “Troitsk 94+96” are obtained accounting for the anomaly.

first five experiments in Table 1 have used magnetic spectrometers. Recent experiments, TROITSK^[3] and MAINZ^[4], use integral electrostatic analyzers, which have achieved an energy resolution of ~ 6 eV. The negative value of m_ν^2 is due to an anomalous excess of the event rate in the vicinity of the end point. TROITSK fitted the observed spectrum assuming an additional spike-like local enhancement near the end-point^[3] and obtained m_ν^2 of -1 ± 6.3 eV².

In this conference, MAINZ experiment has presented the status of 1997 data taking.^[4] The main source of the background in the previous data taking was back-scattered electrons from the source. The background was reduced by putting the T₂ source further upstream of spectrometer and transporting electrons through new guiding magnets. The reduction of the background enable us to increase the source intensity. Thus, the 1997 data was taken between June 23 and August 18 with an increased intensity by a factor of 6, whereas the background level is reduced by 40 % compared with the 1995 data. The resolution of m^2 is expected to be ~ 6 eV² only using the last 70 eV range below the end-point. Results of 1997 data of MAINZ will be published soon.

ALEPH and DELPHI presented tau neutrino mass limits in this conference.^{[5],[6]} ALEPH analyzed $5\pi^\pm(\pi^0)\nu_\tau$ and $3\pi^\pm\nu_\tau$ decay modes.^[5] The two-dimensional analyses of hadron invariant masses and total energies of hadrons gave an up-

per limit of $22.3 \text{ MeV}/c^2$ and $21.5 \text{ MeV}/c^2$ at 95 % C.L. for $5\pi^\pm(\pi^0)\nu_\tau$ and $3\pi^\pm\nu_\tau$ decay modes, respectively. Combining these results, ALEPH obtained an upper limit of $18.2 \text{ MeV}/c^2$. DEPHI analyzed the $3\pi^\pm\nu_\tau$ mode using the invariant mass distribution of three pions.^[6] The observed distribution was fitted using three models: that of Kuhn Santamaria (KS), Isgur Morningstar and Reader (IMR) and Feindt (MF). All models assume that the τ decay proceeds predominantly through the a_1 resonance. The fit by MF model, however, is done adding a resonance with a mass about 1700 MeV and a width of about 300 MeV. a'_1 , a radial excitation of a_1 meson, is a candidate of such resonance. The obtained neutrino mass limits are 33 MeV, 31 MeV and 65 MeV with 95 % C.L. by KS, IMR and MF models, respectively. More study is needed for getting a model independent mass limit.

A zero-neutrino (0ν) mode of double beta decay is possible, if neutrinos have Majorana mass. Recent results of 0ν double beta decay are summarized in Table 2.

Experiment	source/exposure	half-life limit ($\times 10^{24}$ y)	mass limit
Heidelberg-Moscow	$^{76}\text{Ge}/28.7 \text{ Kg}\cdot\text{y}$	> 11 (90 % C.L.)	$< 0.48 \text{ eV}$
UCI TPC	$^{82}\text{Se}/45\text{g}, 21,924 \text{ h}$	> 0.027 (68 %)	$< 4.7 \text{ eV}$
NEMO-2	$^{82}\text{Se}/2.17 \text{ mol}\cdot\text{y}$	> 0.0095 (90 %)	$< 7.9 \text{ eV}$
NEMO-2	$^{100}\text{Mo}/1.18 \text{ mol}\cdot\text{y}$	> 0.0064 (90 %)	$< 6-18 \text{ eV}$
Elegant	$^{100}\text{Mo}/171\text{g}, 7333\text{h}$	> 0.052 (68 %)	$< 2.2 \text{ eV}$
Osburn, USA	$^{100}\text{Mo}/60\text{g}, 3850 \text{ h}$	> 0.044 (68 %)	$< 2.4 \text{ eV}$
NEMO-2	$^{116}\text{Cd}/0.92 \text{ mol}\cdot\text{y}$	> 0.005 (90 %)	$< 10 \text{ eV}$
Elegant	$^{116}\text{Cd}/90\text{g}, 1875\text{h}$	> 0.0063 (68 %)	$< 8.8 \text{ eV}$
Milano, Bolometer	$^{130}\text{Te}/334\text{g}, 9234\text{h}$	> 0.028 (68 %)	$< 4.2 \text{ eV}$
Gotthard	$^{136}\text{Xe}/180 \text{ l}, 2800\text{h}$	> 0.042 (90 %)	$< 1.8 - 2.8 \text{ eV}$

Table 2. Recent results of 0ν double beta decay experiments. Half-life limits of 0ν mode and Majorana neutrino mass limits are shown.

The best limit of Majorana neutrino mass is 0.48 eV (90 % C.L.) obtained by Heidelberg-Moscow experiment.^[7] NEMO-3 detector is under construction and it will start taking data in the end of 1998.^[8] NEMO-3 is able to reach $\sim 10^{25}$ years of half-life limit using 10 kg of ^{100}Mo , which correspond to $\sim 0.1 \text{ eV}$ of Majorana neutrino mass. As a future project of Heidelberg-Moscow experiment, one ton Ge $\beta\beta$ experiment (GENTUS) is being proposed in order to investigate down to 0.01 eV of Majorana mass.^[7]

3 Atmospheric Neutrinos

Atmospheric neutrinos are the decay products of hadronic showers produced by primary cosmic ray interactions in the atmosphere. In recent years, the double-ratio of neutrino events classified by lepton types, $R \equiv (\mu/e)_{DATA}/(\mu/e)_{MC}$, has been studied to approximate the atmospheric neutrino flavor ratio ν_μ/ν_e and to cancel uncertainties in the neutrino flux and cross sections. The measurements of R in underground experiments are summarized in Table 3.

Experiment	exposure (kt·yr)	events	R
NUSEX	0.74	50	$0.96^{+0.32}_{-0.28}$
Frejus	2.0	200	$1.00 \pm 0.15 \pm 0.08$
Kamiokande sub-GeV	7.7	482	$0.60^{+0.06}_{-0.05} \pm 0.05$
Kamiokande multi-GeV	6/8.2	233	$0.57^{+0.08}_{-0.07} \pm 0.07$
IMB	7.7	610	$0.54 \pm 0.05 \pm 0.11$
Soudan-II	2.83	331	$0.61 \pm 0.14^{+0.05}_{-0.07}$
Super-K sub-GeV	20.1	1453	$0.64 \pm 0.04 \pm 0.05$
Super-K multi-GeV	20.1	444	$0.60 \pm 0.05 \pm 0.05$

Table 3. Measurements of R in atmospheric neutrino experiments.^[9]

The results of NUSEX and Frejus gave R close to one. Results of Kamiokande, IMB, Soudan-II and Super-Kamiokande gave significantly small R value. Especially, the high statistical data of Super-Kamiokande re-confirmed the atmospheric neutrino anomaly.

The Super-Kamiokande is a huge water Cherenkov detector located in Kamioka mine in Japan. The detector consists of inner and outer detectors. In the inner-detector, 11,146 photomultiplier tubes(PMT's), each 20 inch in diameter, are uniformly placed facing inward on a 0.707 m grid on the entire surface with dimensions 33.8 m in diameter by 36.2 m high, which contains 32,000 metric tons of water. The total photocathode surface area of all PMT's is 40 % of the surface of the inner-detector. A 4π solid-angle outer-detector surrounds the inner-detector. The outer-detector is also a water Cherenkov counter with 1,885 sets consisting of a wavelength shifter plate and an 8 inch PMT. The thickness of the outer-detector is 2 meters. The outer-detector is designed to reduce external gamma-rays from surrounding rocks and tag cosmic-ray muons. The fiducial volume of the detector is defined to be more than 2 m from the detector wall, which amounts to 22 ktons of water. The data taking of Super-Kamiokande was started in April 1996. Data of 20.1 kt·yr was accumulated between May 1996 and June 1997. The atmospheric

neutrino events are classified into fully contained (FC) events and partially contained (PC) events. The FC events are selected by requiring no hits in outer-detector. The PC events are selected essentially by requiring single outer-detector hit-cluster close to an exit point of the particles observed in the inner-detector. The vertex positions of PC events are required to be in the fiducial volume. In total, 2591 FC events and 156 PC events were observed in the 20.1 kt·yr data sample. The FC and PC events are sub-divided into sub-GeV and multi-GeV events. The selection of sub-GeV events in the FC sample is that (1) visible energy (E_{vis}) is less than 1.33 GeV, (2) momentum is greater than 100 MeV/c for e-like events and 200 MeV/c for μ -like, and (3) maximum pulse height of a single PMT is less than 200 p.e., which rejects events with a particle stopping very close to the detector wall. The multi-GeV events are required to be $E_{vis} > 1.33$ GeV. The number of sub-GeV and multi-GeV events are 1986 and 605 in the FC sample. Then, the events are analyzed through Cherenkov ring number counting program and particle identification program. The misidentification probability of the μ/e separation is estimated to be 1% and 2% in the sub-GeV and multi-GeV samples, respectively. The observed number of single ring e-like and μ -like events are 718 (149) and 735 (139) in sub (multi)-GeV data sample. The all PC events are assumed to be μ -like events. The observed events are compared with a Monte Carlo simulation which uses the flux calculation by Honda et al.^[10] and a neutrino interaction program based on accelerator neutrino experiments.^[11] Nuclear effects, Pauli principle and a mass difference between μ and e are also taken into account in the Monte Carlo simulation. The results of R obtained by using single ring events are shown in Table 3 together with other experiments. The obtained R is significantly smaller than unity and it confirms the results of Kamiokande and IMB results. The zenith angle distributions of observed e-like and μ -like events are shown in Figure 1. As seen in the figure, the upward-going μ -like events are significantly smaller than the MC expectations. It is seen both in the sub-GeV and multi-GeV samples. The distortion of the zenith angle distribution strongly indicates anomaly in the atmospheric neutrinos, because the systematic error of up/down asymmetry of the detector is negligibly small and the shape of the angular distribution cancels various uncertainties in neutrino cross sections, nuclear effects and etc. Possible solution of the anomaly is neutrino oscillations. Using the zenith angle information together with energy information of events, an allowed region of neutrino oscillation parameters is obtained as Fig.2. The overlapped allowed regions of Super-Kamiokande and Kamiokande is around $\Delta m^2 = 5 \times 10^{-3} \text{ eV}^2$ with large mixing angle. The dotted histograms in Fig.1 show expected zenith angle distributions assuming neutrino oscillations of $\nu_\mu \leftrightarrow \nu_\tau$ with parameters of $\Delta m^2 = 5 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta = 1.0$. The neutrino oscillation hypothesis reproduces the observed zenith angle distributions quite well.

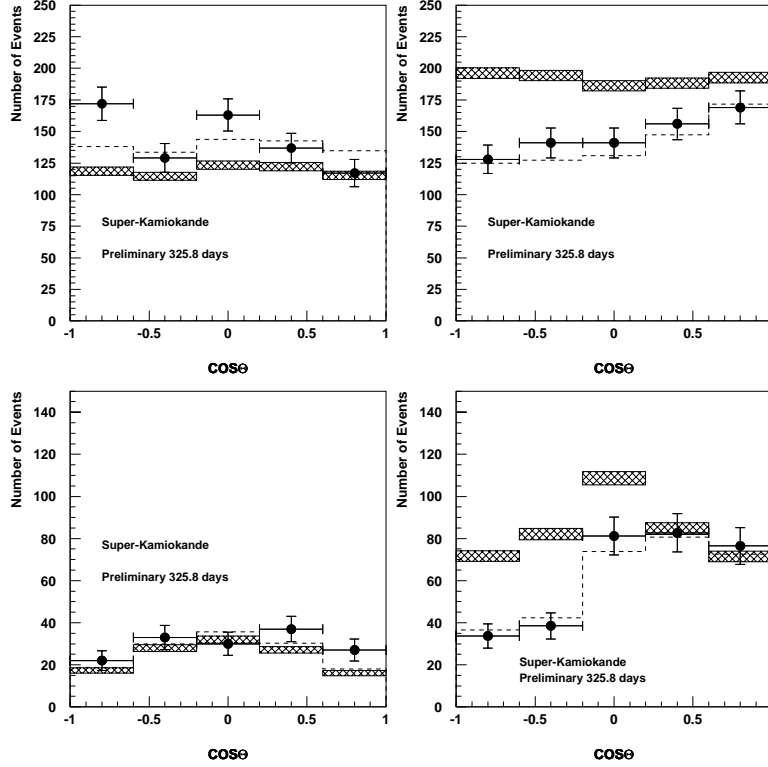


Fig. 1. Zenith angle distributions of e-like and μ -like atmospheric neutrino data in Super-Kamiokande. Upper and lower figures are for sub-GeV and multi-GeV data samples, respectively. $\cos(\theta)=1$ corresponds to downward-going direction. The hatched bands show MC simulation and dotted histograms show the ones assuming $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with $\Delta m^2 = 5 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta = 1.0$.

4 Accelerator neutrino oscillation experiments

The detectors located in the CERN wide band neutrino beamline, CHORUS and NOMAD, had presented their preliminary results in this conference.^{[14],[15]} The salient feature of the CHORUS detector is the 0.8 tons nuclear emulsion target, which enable us to identify τ neutrinos unambiguously. CHORUS searched for $\nu_\mu \rightarrow \nu_\tau$ oscillations using charged current (CC) interactions of ν_τ . 68 % of the τ decay in the nuclear emulsion shows a kink topology through the decay channels of $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$ (1μ) and $\tau^- \rightarrow h^- + \text{neutrals}$ (0μ). 73 % (32 %) of the data taken in 1994 were analyzed for $1\mu(0\mu)$ decay modes and no kink candidate which have more than 250 MeV/c transverse momentum was found. Estimated background is 0.15 events in the analyzed

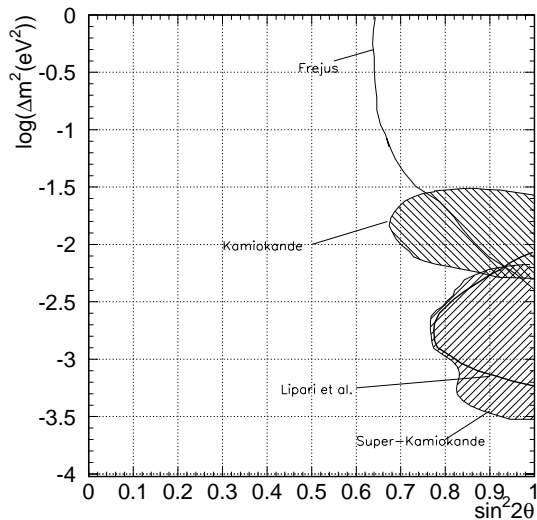


Fig. 2. Allowed regions of neutrino oscillation parameters for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations with 90 % C.L. obtained by atmospheric neutrino data in Super-Kamiokande and Kamiokande. The excluded regions by Frejus^[12] and IMB are also shown.

sample. An obtained limit in the mixing angle is $\sin^2 2\theta_{\mu\tau} < 4.5 \times 10^{-3}$ for large Δm^2 with 90 % C.L. By analyzing the whole data taken from 1994 to 1997, CHORUS is able to reach the sensitivity of 2×10^{-4} in $\sin^2 2\theta$. NOMAD is a detector with extremely good electron identification and charge separation. NOMAD searched for $\nu_\mu \rightarrow \nu_\tau$ oscillations using decay modes of $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$, $\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e$, $\tau^- \rightarrow \pi^- (K^-) \nu_\tau$, $\tau^- \rightarrow \rho^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^- \pi^+ (n\pi^0) \nu_\tau$. No candidate was found in the 1995 data and an upper limit of $\sin^2 2\theta_{\mu\tau} < 3.4 \times 10^{-3}$ (90 % C.L.) was obtained. $\nu_\mu \rightarrow \nu_e$ oscillations were also analyzed in NOMAD using the energy dependence of the ratio of charged current events of ν_e and ν_μ ($R_{e\mu}(E_\nu)$). The observed $R_{e\mu}(E_\nu)$ distribution is consistent with the estimated ν_e contamination of the beam. The result excluded the region of $\Delta m^2 > 10 \text{ eV}^2$ in the LSND allowed region.

LSND group had published a search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations using a $\bar{\nu}_\mu$ beam decay at rest (DAR) as an evidence of neutrino oscillations.^[16] The number of selected events with signatures of $\bar{\nu}_e$ appearance is 22 events in the energy range between 36 MeV and 60 MeV, whereas the estimated background is 4.6 events. Recently, LSND analyzed also $\nu_\mu \rightarrow \nu_e$ oscilla-

tions using ν_μ from π^+ decay in flight (DIF) and an excess of the ν_e events was observed.^[17] The neutrino oscillation probabilities given by LSND are $(3.1 \pm 1.2 \pm 0.5) \times 10^{-3}$ and $(2.6 \pm 1.0 \pm 0.5) \times 10^{-3}$ for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$ analyses. KARMEN had analyzed both oscillation modes using the data till 1995.^[17] Although KARMEN had observed no evidence of the neutrino oscillations, the sensitivity of the detector was not good enough to discuss whole LSND allowed oscillation parameter regions because of cosmic-ray background. In 1996, KARMEN built an additional active veto layer and reduced the cosmic-ray background by a factor of ~ 40 . KARMEN will cover the whole LSND allowed region in 2 - 3 years.

5 Solar neutrinos

Thirty years have passed since Davis started the pioneering solar neutrino experiment. The second generation solar neutrino experiments, Kamikande, GALLEX and SAGE, confirmed the deficit of the solar neutrinos which was first presented by Davis as “solar neutrino problem” (SNP). Now, the third generation experiments, Super-Kamiokande, SNO and BOREXINO are started or under construction. The event rate of first and second generation experiments were < 1 neutrino events per day. The rate was increased to several tens of events per day in the third generation experiments.

Results of currently running solar neutrino experiments are shown in Table-4.

Experiment	method	flux	Data/SSM(BP95)
^{37}Cl	$\nu_e^{37}\text{Cl}$	$2.54 \pm 0.14 \pm 0.14$ SNU	0.27 ± 0.02
GALLEX	$\nu_e^{71}\text{Ga}$	$69.7 \pm 6.7^{+3.9}_{-4.5}$ SNU	0.51 ± 0.06
SAGE	$\nu_e^{71}\text{Ga}$	73^{+10}_{-11} SNU	$0.53^{+0.07}_{-0.08}$
Kamiokande	νe scat.	$(2.80 \pm 0.19 \pm 0.33) \times 10^6$ /cm ² /sec	0.42 ± 0.06
Super-K.	νe scat.	$(2.44 \pm 0.06^{+0.25}_{-0.09}) \times 10^6$ /cm ² /sec	$0.37^{+0.04}_{-0.02}$

Table 4. Results of running solar neutrino experiments.^[19]

The comparisons between the observed fluxes and the expectations from the SSM^[20] are also shown in Table-4. The flux ratio, data/SSM, is small in $\nu_e^{37}\text{Cl}$ experiment and almost half in Gallium experiments. The νe scattering experiments for ^8B neutrinos give data/SSM ~ 0.4 . A detailed study of the relative difference in the flux ratio indicates that the astrophysical solutions have difficulty in explaining SNP.^[21] An analysis on neutrino oscillations shows that the possible solutions of SNP are a small mixing solution (Δm^2

$\sim 0.5 \times 10^{-5} \text{ eV}^2$ and $\sin^2 2\theta \sim 6 \times 10^{-3}$) or a large mixing solution ($\Delta m^2 \sim 1 \times 10^{-5} \text{ eV}^2$ and $\sin^2 2\theta \sim 0.6$).^[21]

Super-Kamiokande (SK) has observed 4395 solar neutrino events during 306 days of live time with an energy threshold of 6.5 MeV. The high statistics data of SK enable us to discuss not only the absolute flux value but also short time variations of the flux, such as day/night effect, and shape of the energy spectrum. Those checks purely depend on properties of neutrinos and are free from any ambiguities in SSM.

The obtained flux difference between day-time and night-time was

$$\frac{\text{Day} - \text{Night}}{\text{Day} + \text{Night}} = -0.017 \pm 0.026 \pm 0.017. \quad (2)$$

The night-time was further sub-divided into five time bins and flux of each bin was compared. No significant variation of flux was observed in the day/night analysis. The result already excludes lower half of the large mixing solution. The analysis of the energy spectrum is in progress. The largest contribution of the systematic errors in the energy spectrum analysis is the uncertainty of the absolute energy scale of the detector. The SK is using electron LINAC for the energy calibration. The current estimate of the energy scale uncertainty is $+4.1$ -1.5 %. By lowering the uncertainty down to 0.5–1.0 %, SK data enable us to discuss small mixing solution only using the shape of the energy spectrum. Further systematic data taking of LINAC will be able to achieve such small uncertainty. Several future solar neutrino experiments are under construction or being proposed. GNO, the upgrade of GALLEX, plans to use 100 tons of Gallium and achieve $\sim 4\%$ accuracy in flux.^[22] ICARUS, which is under construction in Grand Sasso, will detect ^8B neutrino by $\nu_e^{40}\text{Ar}$ interactions.^[23] The HELLAZ is a proposed experiment, which measures the energy spectra of pp and ^7Be neutrinos with νe scattering.^[24] SK, SNO, BOREXINO, and the future solar neutrino experiments will solve the SNP within several years without relying on solar models.

6 Long baseline experiments

The atmospheric neutrino data of several underground experiments indicate neutrino oscillations of $\Delta m^2 = \sim 5 \times 10^{-3} \text{ eV}^2$ with a large mixing angle. To check the oscillations with terrestrial experiments, $L(\text{km})/E(\text{GeV})$ of ~ 100 is needed. Such experiments can be done by long baseline experiments using reactor neutrinos for $\bar{\nu}_e$ disappearance and using accelerator neutrinos for $\nu_\mu \leftrightarrow \nu_X$ oscillations. The summary and status of those experiments are shown in Table-5 and -6.

7 Summary

It is very interesting time for neutrino oscillation physics now. Several underground experiments suggest neutrino oscillations in atmospheric neutrinos

Experiment	Reactor	Distance	Detector	Event rate	Status
CHOOZ	2×4.2 GWth	1.0 km	5t Gd loaded scintillator	25 ev./day	running
Palo Verde	3×3.6 GWth	0.75 km	12t Gd loaded scintillator	50 ev./day	start in fall 1997
Kam-LAND	many reactors	150 km	1000t liquid scintillator	~ 2 ev./day	data taking 2000~

Table 5. Reactor long baseline experiments.^[25]

	K2K ^[26]	MINOS ^[27]	Europe
Baseline	250 km	730 km	730 km
Accelerator	KEK-PS (12 GeV)	FNAL M.I. (120 GeV)	CERN SPS (450 GeV)
Far detector	Super-K.	MINOS	ICARUS, NOE (Gran Sasso)
Event rate	400 CC	140,000 (CC+NC)	1600/1 ICARUS
Status	Construction	R&D	Construction (ICARUS)
Data taking	1999~	~ 2001	> 2000

Table 6. Accelerator long baseline experiments.

and in solar neutrinos. Future experiments should check neutrino oscillations with improved sensitivities, and also neutrino masses themselves should be investigated. A summary of suggested oscillation parameter regions are shown in Fig.3 together with sensitivities of future neutrino oscillation experiments.

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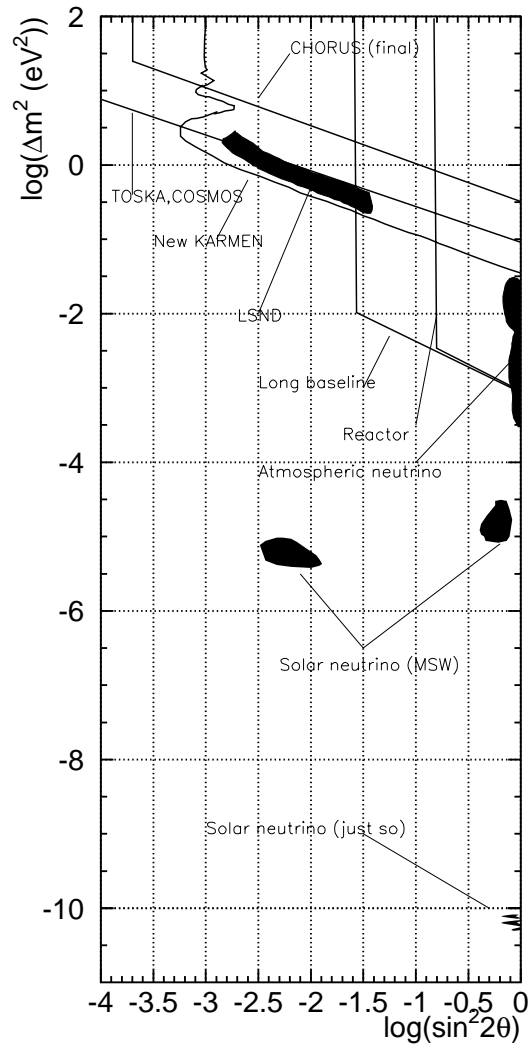


Fig. 3. Suggested oscillation parameter regions shown in filled areas. Sensitivities of future neutrino oscillation experiments are also shown.

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