Long baseline neutrino oscillations

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Abstract
The motivation for possible future long baseline experiments is discussed. The proposed experiments as well as their physics potential is reviewed.
1 Introduction

A non-vanishing neutrino rest mass has far reaching consequences from cosmology down to particle physics [1]. While direct experiments show no hints for such a mass, in the field of neutrino oscillations there is growing evidence. Beside the long standing solar neutrino problem, in the last years growing evidence came up from the LSND-experiment [2] using accelerator neutrinos and from atmospheric neutrinos especially by recent Super-Kamiokande measurements [3]. The scenarios developed to describe the observed effects include the three known neutrinos as well as possible sterile neutrinos [4] not taking part in standard weak interaction. For a compilation of theoretical models see [5].

In a simple two flavour mixing scheme the oscillation probability \( P \) is given by

\[
P(E) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)
\]

with \( \Delta m^2 = |m_2^2 - m_1^2| \), \( L \) the source-detector distance and \( E \) the neutrino energy. The main motivation for long baseline experiments is given by the chance to investigate the large mixing angle solution of the solar neutrinos (\( \nu_e - \nu_X \)) at \( \Delta m^2 \approx 10^{-5} eV^2 \) by using nuclear reactors and to explore the atmospheric neutrino evidence (\( \nu_{\mu} - \nu_X \)) at \( \Delta m^2 \approx 10^{-3} eV^2 \) by using accelerators. The latter not only includes the proof of \( \nu_\mu \) - disappearance but includes a search for \( \nu_\tau \) - appearance. Typical beams at accelerators are produced by protons hitting a fixed target, where the decaying secondaries (mostly pions) decay into \( \nu_\mu \). This dominantly \( \nu_\mu \) beam is then used either for pure \( \nu_\mu \) - disappearance searches or for appearance searches by measuring electrons and \( \tau \)-leptons produced via charged current (CC) reactions. The \( \nu_\tau \) - appearance search requires some beam design optimisation because the exploration of low \( \Delta m^2 \) values prefers lower beam energies but the \( \tau \)-production cross-section shows a threshold behaviour starting at 3.5 GeV and increasing with beam energy (Fig. 1). A possible oscillation of \( \nu_\mu \) into sterile neutrinos might show up in the CC/NC ratio. Independent of the above evidences, effects of a possible CP-phase in the leptonic mixing matrix can be explored by long baseline experiments [6].

2 Reactor experiments

Reactor experiments are disappearance experiments looking for \( \bar{\nu}_e \rightarrow \bar{\nu}_X \). Reactors are a source of MeV \( \bar{\nu}_e \) due to the fission of nuclear fuel. The main isotopes involved are \( ^{235}U \), \( ^{238}U \), \( ^{239}Pu \) and \( ^{241}Pu \). The neutrino rate per fission has been measured for all isotopes except \( ^{238}U \) and is in good agreement with theoretical calculations. Experiments typically try to measure the positron spectrum, which can be deduced from the \( \bar{\nu}_e \) - spectrum, and either compare it directly to the theoretical predictions or measure it at several distances from the reactor and search for spectral changes. Both types of experiments were done in the past. The detection reaction is

\[
\bar{\nu}_e + p \rightarrow e^+ + n
\]

with an energy threshold of 1.804 MeV. Normally, coincidence techniques are used between the annihilation photons and the neutrons which diffuse and thermalize within 10-100 \( \mu s \). The reactions commonly used for neutron detection are \( p(n,\gamma)D \) and \( Gd(n,\gamma)Gd \) resulting in 2.2 MeV gamma photons or gammas up to 8 MeV, respectively. The main background are cosmic ray muons producing neutrons in the surrounding of the detector. With respect to past reactor experiments, the current experiments CHOOZ and Palo Verde can already be considered as long baseline experiments. Their distance to the power stations
of 1030 m and about 800 m respectively is already a factor of at least three larger than any other reactor experiment done before. The results from CHOOZ \(^7\) already exclude \(\nu_\mu - \nu_e\) oscillations as explanation for the atmospheric neutrinos. Long-baseline experiments even by accelerator definitions will be done by KamLAND and BOREXINO.

The KamLAND experiment \(^8\) will be installed in the Kamioka mine in Japan (Fig. 2). It will contain 1000t of Liquid Scintillator as a main target, filled in a plastic balloon which is surrounded by buffer water with a total mass of 2500 t. At the beginning the readout will be done with 1300 20” photomultipliers corresponding to a coverage of 20 %, an upgrade to 2000 might be possible. In total, there are 6 reactors with a total thermal power of 69 GW in a distance between 140 km and 210 km to Kamioka which act as \(\bar{\nu}_e\)-sources. They produce a total neutrino flux of \(10^6 \text{cm}^{-2}\text{s}^{-1}\) at Kamioka which results for a fiducial volume of 0.5 kt and a cut on the electron energy of larger than 3 GeV in an event rate of 250 events/year. This will allow to measure \(\Delta m^2\) as small as \(10^{-5} \text{eV}^2\), therefore probing the large mixing angle solution of the solar neutrino problem. If the background can be reduced by another factor of ten with respect to the proposed value, even the observation of solar \(^7\)Be and terrestrial neutrinos seems feasible.

Originally proposed for solar neutrino detection, also the BOREXINO experiment \(^9\) has the ability to investigate reactor neutrinos. The \(\bar{\nu}_e\)-flux at Gran Sasso Laboratory is around \(1.5 \cdot 10^5\ \text{cm}^{-2}\text{s}^{-1}\) for energies larger than 1.8 MeV produced by power plants typically 800 km away. Without oscillation this would result in 27 events/year in a 300 t liquid scintillation detector. The sensitivity might go down to \(\Delta m^2\) of \(10^{-6} \text{eV}^2\) and \(\sin^2 2\theta > 0.2\).

### 3 KEK- Super-Kamiokande

The first of the accelerator long baseline experiments will be the KEK-E362 experiment (K2K) \(^10\) in Japan sending a neutrino beam from KEK to Super-Kamiokande. It will use two detectors, one about 300 m away from the target and Super-Kamiokande in a distance of about 250 km. The neutrino beam is produced by 12 GeV protons from the KEK-PS hitting an Al-target of \(2\text{cm} \times 65\text{ cm}\). Using a decay tunnel of 200 m and a magnetic horn system for focussing \(\pi^+\) an almost pure \(\nu_\mu\)-beam is produced. The contamination of \(\nu_e\) from \(\mu\) and K-decay is of the order 1 %. The protons are extracted in a fast extraction mode allowing spills of a time width of 1.1 \mu s every 2.2 seconds. With \(6 \cdot 10^{12}\) protons per spill about \(1 \cdot 10^{20}\) protons can be accumulated in 3 years. The average neutrino beam energy will be 1.4 GeV, with a peak at about 1 GeV. The near detector (Fig. 3) consists of two parts, a 1 kt Water-Cerenkov detector and a fine grained detector. The water detector will be implemented with 820 20” PMTs and its main goal is to allow a direct comparison with Super-Kamiokande events and to study systematic effects of this detection technique. The fine grained detector basically consists of four parts and should provide information on the neutrino beam profile as well as the energy distribution. First of all there are 20 layers of scintillating fiber trackers intersected with water. The position resolution of the fiber sheets is about 280 \mu m and allows track reconstruction of charged particles and therefore the determination of the kinematics in the neutrino interaction. In addition to trigger counters there is a lead-glass counter and a muon detector. The 600 lead glass counters are used for measuring electrons and therefore to determine the \(\nu_e\) beam contamination. The energy resolution is about 8% /\(\sqrt{E}\). The muon chambers consist of 900 drift tubes and 12 iron plates. Muons generated in the water target via CC reactions can be reconstructed with a position resolution of 2.2 mm. The energy resolution is about 8-10 %. The detection method within Super-Kamiokande will be identical to that of their atmospheric neutrino detection.

Because of the low beam energy K2K will be able to search for \(\nu_\mu - \nu_e\) appearance and a
general $\nu_\mu$ - disappearance. The main background for the search in the electron channel might be quasielastic $\pi^0$ - production in NC reactions, which can be significantly reduced by a cut on the electromagnetic energy. The proposed sensitivity regions are given by $\Delta m^2 > 1 \cdot 10^{-3} eV^2 (3 \cdot 10^{-3} eV^2)$ and $\sin^2 2\theta > 0.1 (0.4)$ for $\nu_\mu - \nu_e (\nu_\mu - \nu_\tau)$ oscillations.

The beamline should be finished by the end of 1998 and the experiment will start data taking in 1999. In connection with the Japanese Hadron Project (JHP) an upgrade of KEK is planned to a 50 GeV PS, which could start producing data around 2004. The energy of a possible neutrino beam could then be high enough to search for $\nu_\tau$ - appearance, preferably in the $\tau \rightarrow \mu \nu \nu$ decay channel.

4 Fermilab-Soudan

A neutrino program (NuMI) is also associated with the new Main Injector at Fermilab (Fig. 5). The long baseline project will send a neutrino beam to the Soudan mine about 730 km away from Fermilab. Here the MINOS experiment \[\text{(1)}\] will be installed (Fig. 4). It consists of a near detector located at Fermilab about 900 m away from a graphite target and a far detector at Soudan. The far detector will be made of magnetized iron plates, producing a toroidal magnetic field of 1.5 T. They have a thickness of 2.54 cm and an octagonal shape measuring 8 m across, with a transverse granularity of 4.1 cm. They are interrupted by about 32000 m$^2$ active detector planes in form of plastic scintillator strips with x and y readout to get the necessary tracking informations. Muons are identified as tracks transversing at least 5 steel plates, with a small number of hits per plane. The total mass of the detector will be 8 kt. Oscillation searches in the $\nu_\mu - \nu_e$ and $\nu_\mu - \nu_\tau$ channel can be done in several ways. The statistically most powerful way is a $\nu_\mu$ - disappearance search comparing the CC-rate in the near and far detector. Furthermore the NC/CC ratio in the far detector can be used. By using this ratio, information on possible $\nu_\mu - \nu_{\text{sterile}}$ oscillations can be obtained, because $\nu_{\text{sterile}}$ would not contribute to the NC rate as well. A study of the oscillation parameters by itself is possible by investigating the CC and NC visible energy spectra. An additional hybrid emulsion detector for $\nu_\tau$ - appearance is also under consideration. A detector of the size 1 kt working on the same principle as OPERA (see below) would allow a $\tau$ -search on an event by event basis. The final design of the beamline and beam energy is still under investigation depending on the physical goal one wants to achieve. The MINOS-project could start data taking around 2003.

5 CERN-Gran Sasso

A further program considered in Europe are long baseline experiments using a neutrino beam from CERN to Gran Sasso Laboratory \[\text{(2)}\]. The distance is 732 km. The beam protons from the SPS can be extracted with energies up to 450 GeV hitting a graphite target in a distance of 830 m to the SPS. After a magnetic horn system for focusing a decay pipe of 1000 m will follow (Fig. 5).

Several experiments have been proposed for Gran Sasso Laboratory to do an oscillation search. The first proposal is the ICARUS experiment \[\text{(3)}\] which will be installed in Gran Sasso anyway for the search of proton decay and solar neutrinos. This liquid Ar TPC with a modular design, offering excellent energy and position resolution, can also be used for long baseline searches. A prototype of 600 t is approved for installation which will happen in 1999. An update to
3 or 4 modules is planned. Beside a $\nu_\mu$-disappearance search by looking for a distortion in the energy spectra, also an appearance search in the $\nu_\mu - \nu_e$ channel can be done because of the good electron identification capabilities. A $\nu_\tau$-appearance search can be obtained by using kinematical criteria as in NOMAD (Fig. 6). In $\nu_\mu$ and $\nu_e$ CC events the $p_T$ distribution in the plane perpendicular to the beam is balanced between the outgoing lepton and the hadronic final state. The angle $\Phi_{lh}$ between the final state lepton and the hadronic final state is close to 180° and $\Phi_{mh}$, the angle between the hadronic final state and the missing transverse momentum, is more or less uniform distributed. In case of a $\nu_\tau$ CC event, the undetected $\tau$ (only decay products might be observed) will balance the hadronic final state, therefore the absolute value of the missing $p_T$ might be larger and the value $\Phi_{mh}$ will be oriented towards 180° because of the escaping neutrinos. For ICARUS a detailed analysis has been done for the $\tau \rightarrow e\nu\nu$ channel and is under investigation for other decay channels as well.

A second proposal (NOE) [14] plans to build a modular detector consisting of lead-scintillating fiber and transition radiation detectors (TRDs) with a total mass of 6.7 kt (Fig. 7). The calorimeter modules will be interleaved with TRDs of a total mass of 2.4 kt. The TRDs consist of many layers of proportional tubes and polyethylene foam as radiation material. One module consists of 32 layers corresponding to 8192 proportional tubes/module and additional graphite walls, which act as target for neutrino interactions and sum up to 174 t/module. The TRD together with the following calorimeter device allows particle identification as well as energy measurements of electrons, hadrons and muons. The muon energy in the range 1-25 GeV will be determined by multiple $dE/dx$ measurements in the TRD. The complete detector will have twelve modules, each 8m×8m×5m, and at the end one module (muon catcher) for muon identification from interactions in the last part of the detector. Beside the $\nu_\mu$ - disappearance search by measuring the NC/CC ratio this detector allows a $\nu_\tau$ - appearance search, where the $\tau$ decays into $e$, $\mu$ or $\pi$. The search criteria will be similar to the kinematic ones described above.

A third proposal is the building of a 125 kt water-RICH detector (AQUA-RICH) [15], which could be installed outside the Gran Sasso tunnel (Fig. 7). The detector would consist of a 50m×50m×50m cube with a mirror of curvature radius 50 m and a detector plane at 27 m away from the beam entering side. The detector plane can be equipped with 2500 hybrid photodiodes (HPDs) allowing a 20 % coverage and through small holes also the mirror side can contain 625 HPDs corresponding to 5 % coverage. The HPD grid would have a spacing of 1m (2m) at the detector (mirror) plane respectively. Event parameters can be determined from the ring properties, the velocity is given by the ring radius, the direction by the ring center and the momentum by the ring width if the width is determined by multiple scattering (in contrast to normal Cerenkov detectors, where the pathlength determines the ring width). Nevertheless the pathlength can be independently determined by the number of Cerenkov photon hits. Furthermore the focussing of the rings allows multiple ring ($n \lesssim 4$) studies. This detector allows a $\nu_\mu$ - disappearance search in the quasielastic $\nu_\mu n \rightarrow \mu p$ and resonance $\nu_\mu p \rightarrow \mu \Delta^{++}$ channels, a $\nu_\tau$ - appearance search seems feasible by looking at the $\tau \rightarrow \mu \nu \nu$ decay channel. Furthermore a $\nu_\tau$ - appearance search with a 750t iron-emulsion sandwich detector (OPERA) is proposed [16]. Such a detector concept is also under consideration for MINOS as described above. The principle idea is to use iron as a massive target for neutrino interactions and thin emulsion sheets conceptually working as emulsion cloud chambers (ECC) (Fig. 8). The detector could consist of 92 modules, each would have a dimension orthogonal to the beam of $3 \times 3$ m² and in total 30 sandwiches. One sandwich is composed out of 1 mm iron, followed by two 50 μm emulsion sheets, spaced by 100 μm. After a gap of 2.5 mm, which could be filled by low density material, two additional emulsion sheets are installed. Following such a module,
electronic tracking devices will be installed for accurate extrapolation of tracks back into the emulsions. The scanning of the emulsions is done by high speed automatic CCD microscopes. The $\tau$, produced by CC reactions in the iron, decays in the gap region, and the emulsion sheets are used to verify the kink of the decay. Besides the $\tau \to e, \mu, \pi$ decay modes also three pion decays can be examined. The analysis here is done on an event by event basis. The tracking devices might also allow a $\nu_\mu - \nu_e$ oscillation search. Finally, there is a proposal (NICE) [17] for a 10 kt iron-scintillator calorimeter, surrounded by a magnetized iron spectrometer. The modular design would be done with long iron and scintillator bars, dimensions of 12 m $\times$ 2 cm $\times$ 2 cm seem feasible, building up a total detector of 12 m $\times$ 12 m $\times$ 8 m. The scintillator is read out by wavelength shifting thin fibers, which could be coupled to devices like HPDs. The oscillation searches focus on the measurement of the energy spectra for $\nu_\mu$ - disappearance searches and on measuring the CC/NC ratio. Ideas to merge the OPERA and NICE concepts are under consideration.

6 Very future projects

A project in the very far future could be oscillation experiments involving a $\mu^+\mu^-$-collider currently under investigation. The created neutrino beam is basically free of $\nu_\tau$ and can be precisely determined to be 50% $\nu_\mu(\bar{\nu}_\mu)$ and 50% $\bar{\nu}_e(\nu_e)$ for $\mu^-(\mu^+)$. The collider could be constructed out of 2 straight sections connected by two arcs, where the straight regions are used as decay regions of the muons, producing a neutrino beam in the corresponding direction. Because the $\mu^+\mu^-$-collider would be a high luminosity machine there could be a production rate for neutrinos of $10^{20}$/year. Thus one even can envisage very long baseline experiments, e.g. from Fermilab to Gran Sasso with a distance of 9900 km [18]. The interaction rate in a far 10 kt detector would be of the order 600 $\bar{\nu}_\mu$ per year and 1000 $\nu_e$ per year, assuming the decay of $\mu^+$ is used for the beam.

An even more ambitious idea is to use detectors designed for very high energy neutrino astrophysics. Several astrophysical sources are considered for neutrino production even beyond 1 PeV. At these energies the interaction length for neutrinos becomes less than the diameter of the earth. While $\nu_\mu$ and $\nu_e$ entering the earth from the far side with respect to a detector will be damped, the $\nu_\tau$ flux remains flat because with every $\tau$ - production a new $\nu_\tau$ will be created. This leads to a more or less constant zenith angle dependence for $\nu_\tau$. Some discovery potential might exist with the AMANDA or planned ICECUBE detector, which could investigate very small $\Delta m^2$ because of the long baseline due to the distance of the astrophysical sources.

7 Summary and conclusions

The present evidences for neutrino oscillations and their description in theoretical models requires a variety of new experiments for confirmation. Several proposals for accelerator based long baseline experiments are available to explore the atmospheric region of evidence. In their present design most of them will fail to investigate the complete $\Delta m^2$ region given by Super-Kamiokande especially at low $\Delta m^2$ (Fig. 9). Furthermore nuclear reactors will allow to probe one of the solutions to the solar neutrino problem directly. Together with running and planned short baseline experiments it might be possible to merge into a coherent picture of neutrino mass models in the future.
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Figure 1: Left: Cross-section for $\nu_\mu$ (upper curve) and $\nu_\tau$ (lower curve) CC reactions as function of $E_\nu$. Right: Ratio of both cross-sections, the threshold behaviour of $\sigma_\tau$ is clearly visible.

Figure 2: Principle layout of the KamLAND detector currently under installation in the Kamioka mine. A plastic balloon filled with 1000t of Liquid Scintillator is surrounded by water as buffer liquid and a grid of 1300 20" photomultiplier.

Figure 3: Schematic design of the near detector in the K2K-experiment. The neutrino beam is entering from the right side, passing through a 1 kt Water-Cerenkov detector and a second fine grained detector. For details see text.
MINOS (Main Injector Neutrino Oscillation Search)
Far (Labyrinth) Detector

Fermilab

32,000 m Active Detector Planes
x and y strip/wire readout
480,000 channels

Magnet coil

Magnetized Fe Plates
600 Layers x 2.54 cm Fe
8.0 kT Total Mass

Figure 4: Layout of the MINOS detector installed in the Soudan-mine.

Figure 5: Left: Layout of the neutrino beam from CERN to Gran Sasso (NGS). Right: The NuMI beam design at Fermilab.

Figure 6: Definition of the kinematic variables used in some long baseline experiments for $\nu_\tau$ appearance searches. For details see text.
Figure 7: Left: Layout of the new designed NOE-module consisting of several TRDs and a calorimeter device. Right: Principal layout of the AQUA-RICH detector. The neutrino beam is entering a 50 m cube containing 125 kt of water from the left side. The mirror plane (dots) and detector plane (black) are shown as well.

Figure 8: Principle idea of the OPERA concept. A $\tau$-lepton produced via CC in the iron is reaching an air gap as decay area. Using the emulsion sheets (ES) the mismatch of the track from the $\tau$ and the one from its decay product can be seen.

Figure 9: Principle $\sin^22\theta$ vs. $\Delta m^2$ exclusion plots of the proposed long baseline experiments. Shown is the atmospheric neutrino region as well as given or proposed exclusion plots for $\nu_\mu - \nu_X$ (left) and $\nu_\mu - \nu_e$ (right) oscillations.