STATUS AND PERSPECTIVES OF NEUTRINO OSCILLATION SEARCHES [a]

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The current status of neutrino oscillation searches with reactors and accelerators is reviewed. An outlook, especially on future long baseline neutrino oscillation projects, is given.

1   Introduction

The existence of massive neutrinos opens up a variety of new phenomena which could be investigated by experiments. One of these is neutrino oscillations. In the simplified picture of two flavour oscillations they can be parametrized by two parameters, $sin^2 2\theta$ and Δm^2. While $sin^2 2\theta$ describes the amplitude of the oscillation, $\Delta m^2 = m_2^2 - m_1^2$ determines the oscillation length L given in practical units as

$$L = \frac{4\pi E \hbar}{\Delta m^2 c^3} = 2.48 (\frac{E}{MeV})(\frac{eV^2}{\Delta m^2}) \quad m \tag{1}$$

As can be seen, oscillations do not allow an absolute mass measurement and neutrinos must not be exactly degenerated. For a general discussion of direct mass bounds and on physics with massive neutrinos see [1]. From first principles, there is no preferred region in the $\Delta m^2 - sin^2 2\theta$ parameter space and therefore the whole has to be investigated experimentally.
On earth, two artificial neutrino sources exist in form of nuclear power reactors and accelerators. For a more detailed overview see [2].

2   Reactor experiments

Reactor experiments are looking for $\bar{\nu}_e \rightarrow \bar{\nu}_X$ disappearance. Reactors are a source of MeV $\bar{\nu}_e$, due to the fission of nuclear fuel. 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 distortions. Both

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types of experiments were done in the past. The detection relies on the reaction

$$\bar{\nu}_e + p \to e^+ + n \tag{2}$$

with an energy threshold of 1.804 MeV. Different strategies are used for the detection of the positron and the neutron. Normally, coincidence techniques are used between the annihilation photons and the neutrons which diffuse and thermalise within 10-100 μs and materials like Gd are then used for neutron-capture. The most recent experiment is CHOOZ in France [3]. Compared to previous experiments, this detector has some advantages. First of all, the detector is located underground with a shielding of 300 mwe, reducing the background due to cosmics by a factor of 300. Moreover, the detector is about 1030 m away from the reactor (more than a factor 4 in comparison to previous experiments) enlarging the sensitivity to smaller Δm^2. In addition, the main target has about 4.8 t of a specially developed Gd-loaded scintillator and is therefore much larger than those used before. First results can be seen in Fig.1. An experiment with similar goals is the Palo Verde (former San Onofre) experiment [4] near Phoenix, AZ (USA). It consists of a 12 t liquid scintillator also loaded with Gd. The experiment is located under a shielding of 46 mwe in a distance of about 750 (820) m to the reactors. The experiment started data taking recently.

A first long-baseline reactor experiment (KamLAND) [5] using a 1000 t liquid scintillator detector at the Kamioka site in a distance of 150 km to a reactor is approved by the Japanese Government. It could start data taking in 2000.

3   Accelerators

Accelerators typically produce neutrino beams by shooting a proton beam on a fixed target. The produced secondary pions and kaons decay and create a neutrino beam dominantly consisting of ν_μ. The detection relies on charged current reactions $\nu_i N \to i + X$ $(i = e, \mu, \tau)$, where N is a nucleon and X the hadronic final state. Depending on the intended goal, the search for oscillations therefore requires a detector which is capable of detecting electrons, muons and τ - leptons in the final state. Accelerator experiments are mostly of appearance type working in the channels ν_μ - ν_X and ν_e - ν_X.

3.1   Accelerators at medium energy

At present there are two experiments running with neutrinos at medium energies ($E_\nu \approx$ 30 - 50 MeV) namely KARMEN [6] and LSND [7]. LSND finds evidence for oscillations in the ν_e - ν_μ channel for pion decay at rest and in flight. To
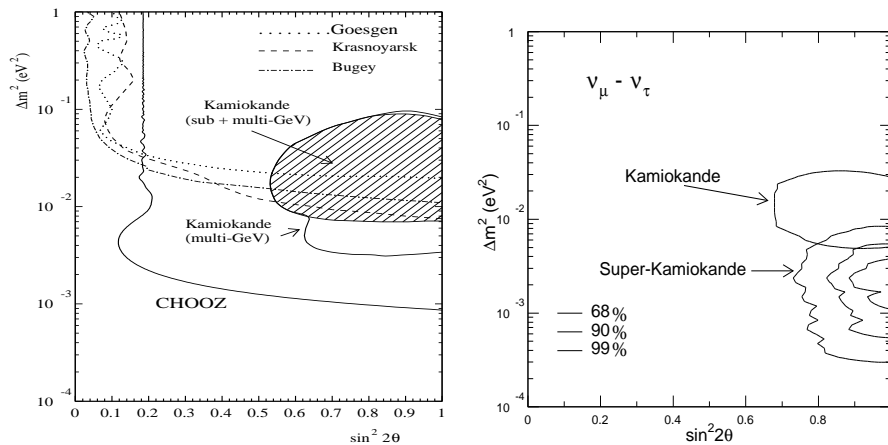
Figure 1: *Left: Exclusion plot for $\bar{\nu}_e$ - $\bar{\nu}_X$ oscillation as given by the CHOOZ-results and other reactor experiments. Also shown are the allowed regions from atmospheric neutrinos given by Kamiokande. As can be seen, the complete region is excluded. Right: 68 %, 90 % and 99 % confidence intervals for ν_μ - ν_τ oscillation necessary to explain the atmospheric neutrino deficit as observed by Superkamiokande in their 33.0 kt·y data sample. The Kamiokande 90 % region is shown for comparison.*

improve the sensitivity for oscillation searches by reducing the neutron background KARMEN constructed a veto shield against atmospheric muons which has been in operation since Feb.1997 and is surrounding the whole detector. The limits reached so far and the LSND evidence are shown in Fig.2. The new analysis of KARMEN seems to be in contradiction with the LSND evidence. While LSND will stop data aquisition after 1998, KARMEN will continue until 2000.

To test the LSND region of evidence several new projects are planned. The Fermilab 8 GeV proton booster offers the chance for a neutrino experiment as well which could start data taking in 2001. It would use part of the LSND equipment and will consist of 600 t mineral oil to be located 500 m away from the neutrino source (MiniBooNE)[8]. An extension using a second detector at 1000m is possible (BooNE). An increase in sensitivity in the ν_e - ν_μ oscillation channel could also be reached by a proposed experiment at the CERN PS[9] or if there is a possibility for neutrino physics at the planned European Spallation Source (ESS) or the National Spallation Neutron Source (NSNS) at Oak Ridge which might have a 1 GeV proton beam around 2004.
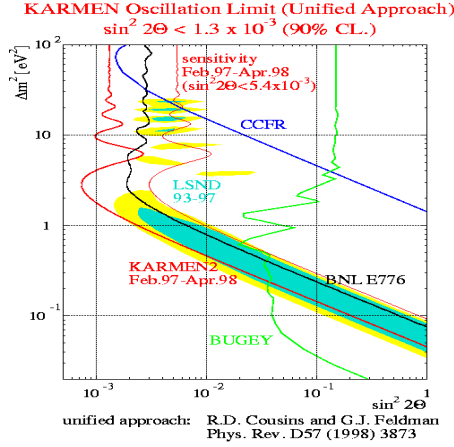
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Figure 2: *Region of evidence for $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillations from LSND together with already excluded parts from KARMEN, E776, CCFR and the Bugey reactor experiment.*

3.2 Accelerators at high energy

High energy accelerators provide neutrino beams with an average energy in the GeV region. Here, at present especially CHORUS and NOMAD at CERN are providing new limits [10]. Both experiments are 823 m (CHORUS) and 835 m (NOMAD) away from a beam dump and designed to improve the existing limits on ν_μ - ν_τ oscillations by an order of magnitude. The present limits (Fig.4) for large Δm^2 are [10]

$$sin^2 2\theta < 1.3 \times 10^{-3} \quad (90\%CL) \quad (CHORUS) \tag{3}$$

$$sin^2 2\theta < 2.2 \times 10^{-3} \quad (90\%CL) \quad (NOMAD) \tag{4}$$

The final goal is to reach a sensitivity down to $sin^2 2\theta \approx 2 \times 10^{-4}$ for large Δm^2. Having a good electron identification NOMAD also offers the possibility to search in the ν_e - ν_μ channel. While the CHORUS data taking is finished, NOMAD continues 1998.

4 Future accelerator experiments

Possible future ideas split into two groups depending on the physical goal. One part is focussing on improving the existing bounds in the eV-region by another order of magnitude with respect to CHORUS and NOMAD and to

investigate the LSND evidence. Other groups plan to increase the source - detector distance to probe smaller Δm^2 and to be directly comparable to atmospheric scales. The last point is of special importance because of the recent claim of evidence for ν_μ - ν_τ oscillations in the atmospheric neutrino data by Super-Kamiokande [11], which are shown in Fig.1 and 3.
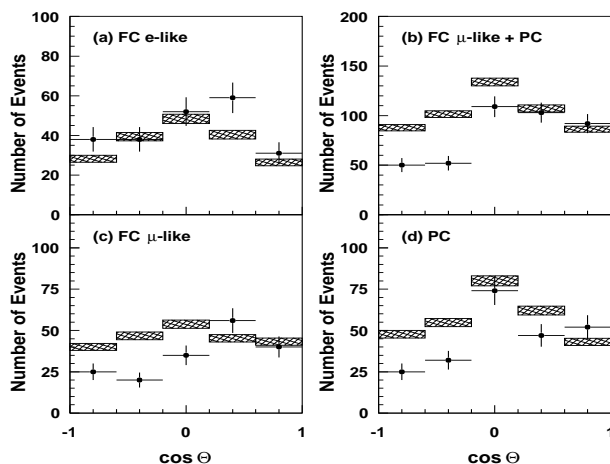

Figure 3: *Zenith angle distribution of a) FC e-like events b) FC μ-like and PC events c) FC μ-like and d) PC events as observed with Superkamiokande . The statistical significance corresponds to 25.5 kt·y. Vertical downward going events correspond to cosθ = 1, vertical upward going to cosθ = −1. The shaded boxes are the MC predictions including the statistical uncertainties.*

4.1 Short and medium baseline experiments

Ideas exist for a next generation of short or medium baseline experiments. At CERN the follow up is TOSCA [12], combining features of NOMAD and CHORUS. The idea is to use 2.4 tons of emulsions together with large silicon microstrip detectors within the NOMAD magnet. For TOSCA the option to extract a neutrino beam at lower proton energies (350 GeV) at the CERN SPS exist. The proposed sensitivity in the ν_μ - ν_τ channel is around 2×10^{-5} for large Δm^2 ($\Delta m^2 > 100 eV^2$) (Fig.4) and data taking could start at the beginning of the next century. Also proposals for a medium baseline search exist [13,14]. The present CERN neutrino beam is coming up to the surface again in a distance of about 17 km away from the beam dump offering the chance for an experiment there.
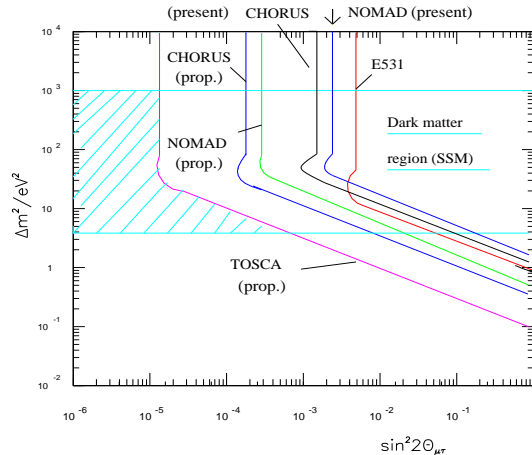
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Figure 4: ν_μ - ν_τ exclusion plot showing the present limits of CHORUS and NOMAD as well as the proposed limits of CHORUS, NOMAD and TOSCA. The shaded area corresponds to the signal region if there is a ν_τ in the eV-range as motivated by dark matter considerations and assuming the quadratic see-saw-mechanism (SSM).

4.2   Long baseline experiments

Several accelerators and underground laboratories around the world offer the possibility to perform long baseline experiments , a search which is strongly motivated by the new results on atmospheric neutrinos . Because the region of evidence moved towards smaller Δm^2 by roughly one order of magnitude most of the experiments reconsider their design.

KEK - Superkamiokande : The first of these experiments will be the KEK-E362 (K2K) experiment [15] in Japan sending a neutrino beam from KEK to Superkamiokande . The distance is about 235 km. A near detector, about a 1 km away from the beam dump, will consist of two detectors, a 1 kt water Cerenkov-detector and a further detector consisting of a SciFi/water target followed by trigger counters, a lead glass calorimeter and a muon-detector. They will serve as a reference and measure the neutrino spectrum. The neutrino beam with an average energy of 1.4 GeV is produced by a 12 GeV proton beam dump. The detection method within Superkamiokande will be identical to that of their atmospheric neutrino detection. The beamline should be finished by the end of 1998 so the experiment could start data taking in 1999. The experiment is of disappearance type. However an upgrade of KEK to a 50 GeV proton beam is planned, which could start producing data around 2004

and would allow ν_τ -appearance searches.

Fermilab - Soudan: A neutrino program is also associated with the new Main Injector at Fermilab. The long baseline project will send a neutrino beam to the Soudan mine about 735 km away from Fermilab. Here the MINOS experiment [16] will be installed. It consists of a near detector located at Fermilab and a far detector at Soudan. The far detector will be made of 8 kt magnetized Fe toroids in 600 layers with 2.54 cm thickness interrupted by about 32000 m^2 active detector planes in form of plastic scintillator strips to get the necessary tracking informations. An additional hybrid emulsion detector for τ-appearance is also under consideration. The final beam line layout is still under investigation. The project could start at the beginning of next century.

CERN - Gran Sasso: A further program in Europe considers long baseline experiments using a neutrino beam from CERN to Gran Sasso Laboratory. The distance is about 732 km. Several experiments have been proposed for the oscillation search. The first proposal is the ICARUS experiment [14] which will be installed in Gran Sasso anyway for the search of proton decay and solar neutrinos by using a liquid Ar TPC. A prototype of 600 t is approved for installation in 1999. An upgrade to about 3 kt is foreseen. A second proposal, the NOE experiment [17], plans to build a giant combination of lead - scintillating fibre and transition radiation detectors with a total mass of 6.7 kt, followed by a module for muon identification. A third proposal is a 125 kt water-RICH detector (AQUA-RICH) [18], which could be installed outside the Gran Sasso tunnel. It could be independently used for measuring atmospheric neutrinos. Finally there exists a proposal for a 750 t iron-emulsion sandwich detector (OPERA) [19]. It would use thin iron plates as target as well as emulsion sheets for tracking purposes. The τ-decay would happen in an air gap between the emulsions.

5 Summary and Conclusion

Massive neutrinos allow a wide range of new phenomena in neutrino physics, especially that of neutrino oscillations. Evidence for such oscillations comes from solar neutrinos, atmospheric neutrinos and the LSND experiment. The Δm^2 regions allowed are around 1 eV^2 (LSND), around $10^{-2}-10^{-3}eV^2$ (atmospheric) and $10^{-5}eV^2$ (MSW, solar) or $10^{-10}eV^2$ (vacuum, solar). Terrestrial neutrino experiments in form of nuclear reactors and high energy accelerators already exclude large parts of the parameter space because of non-observation of oscillation effects. Because the region of the MSW-solution for solar neutrinos are out of range for terrestrial experiments, current and to a large ex-

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tend future oscillation experiments are motivated by the atmospheric neutrino deficit, an eV-neutrino as dark matter candidate and a proof of the LSND results. Long-baseline experiments are necessary to explore the atmospheric region of evidence but might fail to explore it completely.

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