Planned reactor and beam experiments on Neutrino Oscillations

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Abstract

Current and future neutrino oscillation experiments are discussed with an emphasis on those that will measure or further limit the neutrino oscillation parameter θ_{13}. Some ν_e disappearance experiments are being planned at nuclear reactors, and more ambitious $\nu_\mu \rightarrow \nu_e$ appearance experiments are being planned using accelerator beams.

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1. Interest in θ_{13}

In the standard 3 neutrino paradigm, the MNS mixing matrix is parametrized by three mixing angles and one CP phase. Two mixing angles, θ_{12} and θ_{23} have been measured. Limits on the third mixing angle θ_{13} have been reported and the most stringent limit comes from the CHOOZ reactor neutrino experiment[1]. A variety of future reactor experiments are planned which hope to measure θ_{13} or further limit it. There are many ideas for future accelerator-based neutrino experiments on several time scales. If θ_{13} is large enough, these could make measurements that would shed light on the neutrino mass hierarchy and on the CP phase.

There is a large range of ideas for neutrino oscillation measurements. Experiments running in existing beams are MINOS, OPERA and ICARUS. Near-term reactor experiments are Double Chooz, RENO and Daya Bay. Mid-term accelerator projects are T2K and NOνA . Ideas for later projects include T2HK, T2KK, MODULAR/LAGUNA, FNAL-DUSEL, INO, Neutrino Factories and Beta Beams. Other relevant projects are

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KamLAND, HANO-HANO, further solar and atmospheric neutrino measurements, supernova measurements, and future larger reactor neutrino experiments such as Triple Chooz. I can only mention a few of these projects here. Some of the others are covered in Reference [3].

2. The current limit on θ_{13}

The best current limit on θ_{13} comes from CHOOZ[1]. That experiment sought to test whether or not the atmospheric neutrino anomaly could be explained by $\nu_\mu \to \nu_e$ oscillations. In today's language, they were searching for a value of θ_{12} which could have explained the apparent deficit of ν_μ in atmospheric neutrinos. Their limit is shown in Figure 1. It could be interpreted as a limit on both θ_{12} and θ_{13}. We now know that results related to atmospheric neutrinos are explained by θ_{23}, to which CHOOZ was not sensitive, and that θ_{12} can only be measured at lower values of Δm^2. The CHOOZ result does provide a useful limit on θ_{13} but it is clearly a steep function of Δm^2 in the region suggested by Super-Kamiokande, as indicated in Figure 1.

One encounters a variety of numbers which are described as the "CHOOZ limit" for θ_{13}. There are two reasons for this. They both relate to the fact that the limit is a function of Δm^2_{32}. One is that the best value of Δm^2_{32} has evolved as Super-Kamiokande reported on larger data sets, and K2K and MINOS have provided measurements. The other reason is that some choose to quote the limit at a best-fit value of Δm^2_{32}, while a more conservative approach is to use the one-sigma low value. Neither number is a real 90% CL upper limit, taking into account our uncertainty in the value of both parameters. The PDG has adopted the latter view and the 2008 version specifies $\sin^2(2\theta_{13}) < 0.19$. A global neutrino analysis in Reference [4] finds two hints for a small but non-zero θ_{13}, consistent with this limit. One involves small differences between the best fit by KamLAND and solar neutrino experiments. The other is bit more controversial, and involves the electron-like atmospheric neutrino data. I mention this not to emphasize the correctness of this interpretation, but to show that additional solar and atmospheric data is still quite valuable.

3. Comparing reactor and accelerator search strategies

Since the best current limit on θ_{13} comes from a reactor experiment, it is natural to ask how such an experiment could be improved. The obvious answer is to use a near detector to cancel systematic errors, as first proposed by KR2DET[5] and developed by an International Working Group in 2004[6]. The oscillation probability $1 - P(\bar{\nu}_e \to \bar{\nu}_e)$ is:

$$\cos^4\theta_{13}\sin^2 2\theta_{12}\Delta_{21} + \sin^2 2\theta_{13}[\sin^2\theta_{12}\sin^2\Delta_{32} + \cos^2\theta_{12}\sin^2\Delta_{31}]$$

where $\Delta_{ij} = (m_i^2 - m_j^2)L/4E$. For reactor neutrinos with $E \sim 4$ MeV, this simplifies to

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

within a few km. The vacuum equation for the accelerator appearance, sometimes called the subdominant mode, is more complicated[2], and for long-baseline experiments which traverse much earth, matter effects can be important as well. A long-baseline experiment which makes an exact measurement of $P(\nu_\mu \rightarrow \nu_e)$ using both neutrinos and antineutrinos can still have an 8-fold ambiguity in the determination of θ_{13}, depending on the value of δ, the mass hierarchy, and the value of θ_{23}. These issues do not affect reactor experiments. This makes them advantageous as a method for measuring θ_{13}, but disadvantageous since they are insensitive to other important physics. Reactor experiments involve measuring the difference between two similar numbers, so careful control of systematics will be required. Detector sizes in the tens of tons will be needed, and the detectors will need to be shielded from cosmic rays with 100 m or more of rock. Accelerator experiments are looking for the appearance of ν_e, so the control of backgrounds becomes more important than most other systematic issues. The ratio of signal to background improves by going a few degrees off-axis from the center of the beam. But event rates are quite low, and detector sizes of tens of kilotons will be needed. The required overburdens are less clear, and NOνA will try to build an experiment near the surface.

4. Reactor Experiments

The Double Chooz[10], Daya Bay[11] and RENO[12] experiments are the next generation of reactor neutrino searches, all building detectors based on the designs in Reference [6]. A cylinder containing phototubes will be used to watch three volumes of liquid: 1) a target of gadolinium-loaded liquid scintillator, enclosed in 2) a "γ-catcher" volume of scintillator without gadolinium and 3) a buffer containing mineral oil without scintillator. The measure of luminosity for such an experiment is measured in Gigawatt-ton-years (GTY), consisting of the reactor power times the mass of the far detector and the running time. The CHOOZ experiment ran for 12 GTY. The sensitivity versus luminosity was studied in Reference [7] and is shown in Figure 2. The solid curve shows a reasonable goal for systematic errors of 0.8% normalization and 0.5% relative energy calibration. A large gain can be quickly achieved with an experiment of a few hundred GTY, but beyond that, statistics will need to be increased by another order of magnitude, and/or systematic errors will need to be precisely controlled.

The Double Chooz reactor neutrino experiment will be the next detector to search for a non-vanishing θ_{13}[8]. The measurement of this angle will be based on a precise comparison of the antineutrino spectrum at two identical detectors located at different distances from the Chooz nuclear reactor cores in France. Double Chooz will explore $\sin^2(2\theta_{13})$ down to 0.03 at 90% CL for $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 in three years of data taking with both detectors. The installation of the far detector started in May 2008 and the first neutrino data are expected in 2009. Data taking with both the far and near detectors should start in 2011.

5. Results from MINOS

Detailed results from the MINOS experiment which uses the NuMI beamline at Fermilab are presented elsewhere in these proceedings[13]. The most important recent result from MINOS is a measurement of $\Delta m^2_{32} = (2.43 \pm 0.13) \times 10^{-3} eV^2$ (68% CL) based on a measurement of the energy distribution of charged current events at the far detector. The energy distribution that would be expected in the absence of oscillations is mea-

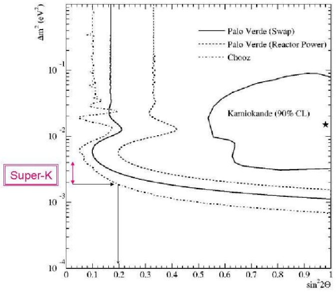

Fig. 1. The CHOOZ limit and the allowed region for θ_{13} based on Δm^2 from Super-Kamiokande. Taken from Reference [9].

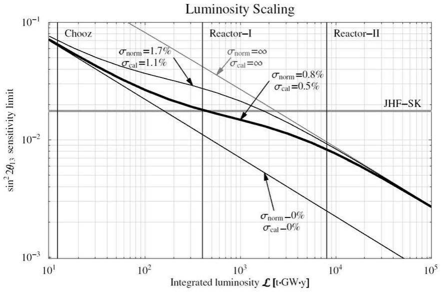

Fig. 2. Luminosity scaling of the θ_{13} limit for a two detector reactor experiment.

sured in a similar near detector located on the Fermilab site. This result is based on 3.21×10^{20} protons-on-target (POT) using data recorded between May 2005 and July 2007. The allowed MINOS parameter space in $\sin^2 2\theta$ and Δm^2, including systematic errors, is shown in Reference [13] along with a previous MINOS result and other high precision experiments[14].

Currently there is an intense analysis within MINOS for $\nu_\mu \rightarrow \nu_e$ appearance and a result based on 3.25×10^{20} POT is expected in early 2009. The expected sensitivity is shown in Reference [13], and for many values of the CP violation parameter δ, it is slightly better than the CHOOZ limit[2]. Another major current analysis of MINOS is to measure the $\nu_\mu \rightarrow \nu_\tau$ parameters with antineutrinos. This could be done either using the antineutrinos in the current MINOS beam, or with future dedicated antineutrino running, i.e. with the horn current reversed to focus π^- and K^-. Again, results and sensitivities are expected in early 2009.

6. NOνA

NOνA is a new Fermilab project to put an off-axis detector in the NuMI beam. NOνA is designed to search for $\nu_\mu \rightarrow \nu_e$ appearance by comparing electron neutrino rates at Fermilab with the rates observed in a large detector 810 kilometers from Fermilab. A search for this oscillation channel has three main backgrounds: 1) ν_e in the beam; 2) ν_μ NC and CC events which cannot be distinguished in the detector from an electron shower; and 3) $\nu_\mu \rightarrow \nu_\tau$ oscillation where the τ decays into an electron. Due to a variety of kinematic effects, all three of these backgrounds become less important when you go off-axis of the neutrino beam, even when you take into account the lower average neutrino energy and flux, which lead to a lower event rate.

As currently envisioned[15], the 15 kiloton NOνA far detector will be composed of 385,000 cells of extruded PVC plastic in a cellular structure. Each cell will be 3.9 centimeters wide by 6.0 centimeters deep and 15.5 meters long. The cells are filled with 3.3 million gallons of liquid scintillator. The liquid scintillator comprises 70% of the total detector mass, making it a totally active tracking calorimeter, optimized for identification of ν_e interactions. The detector will be read out by 0.7 mm diameter optical wave-shifting fiber into 12,000 avalanche photodiodes. A 222 ton Near Detector will be constructed with identical components.

NOνA will be sensitive to θ_{13} and also the mass hierarchy and CP violation in a complicated way. Event rates and backgrounds also depend on θ_{12}, θ_{23}, Δm^2_{32} and the mass hierarchy. The most recent sensitivities for NOνA can be found in Reference [16].

During the dramatic FY2008 budget jolts to HEP in the US, the fate of NOνA itself went through some dramatic oscillations. Fermilab had approved and given some funding to the construction, but the December 2007 continuing resolution specifically provided zero funds and stopped much work on the project. A supplemental appropriation in the summer provided some money to continue, but the initial continuing resolution for FY2009 led the DOE to state that NOνA could be canceled if that was the final budget for 2009. As this article is being written, however, most activities on NOνA have resumed, and there is cautious optimism that NOνA will continue.

7. DUSEL and LB-DUSEL

The Deep Underground Science and Engineering Lab (DUSEL) is a proposed new facility at the site of the former Homestake mine and Davis Solar Neutrino Experiment in South Dakota where a large amount of space for underground science in the US is planned. The possibility of a large multi-purpose detector at DUSEL that could serve as a new long-baseline neutrino detector, as well as other fundamental particle physics such as proton decay, was attractive to the 2008 P5 panel. I will here quote three places from their report[17]:

“The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab.”

“The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D on the technology for a large detector at DUSEL.”

“The panel further recommends that in any funding scenario considered by the panel, Fermilab proceed with the upgrade of the present proton source by about a factor of two, to 700 kilowatts, to allow a timely start for the neutrino program in the Homestake Mine with the 700-kilowatt source.”

The upgrade to 700 KW is part of the NOνA project, and has been also known as ANU (for Accelerator project for NeUtrinos.) The further upgrade to a multi-megawatt proton source has been previously known as the proton driver, but currently is called Project X. Whatever the future neutrino program at Fermilab, increased proton intensities are a logical component of that program, and a variety of scenarios, too long to describe here, have been considered.

An LB-DUSEL collaboration is forming to design and implement the beam and detector required for a long-baseline physics program from Fermilab to DUSEL. Much of the physics case has been described in several documents. For example, see Reference [18].

A specific configuration for a long-baseline detector could be three cavities for water Cherenkov detectors, with each one containing a fiducial volume of 100 kilotons. Preliminary engineering drawings for this configuration at the 4850 level are being developed.

P5 emphasized that the idea for a new long-baseline project from Fermilab to DUSEL was a vision, not a plan. It consists of several parts, which can alternately be regarded as a strength and a weakness. To put a scale on the vision, I have attached my own cost estimates to some of the parts, with all the dangers and none of the required caveats: 1) DUSEL which is a $500M+ facility; 2) A new beam line at Fermilab; $250M; 3) Project X; $1B; and 4) A new huge detector; ($500M-$1B). None of these components currently exist or are approved. However, all elements of the vision have independent motivations, and could be part of a future US HEP roadmap if there is the continued scientific motivation and will to do so.

8. Other ideas for long-baseline experiments

There are other ideas for using conventional neutrino beams in the U.S., Europe and Japan, and very-long baselines could be useful, such as a beam aimed at the Indian Neutrino Observatory planned in India. Many scientists are participating in an international effort to consider coupling a muon storage ring to a neutrino factory, which could be a source of both high energy ν_μ and ν_e for oscillation studies. There is also considerable effort in Europe and elsewhere to consider the potential of building Beta beams, where storage rings of radioisotopes could be sources of ν_e or $\bar{\nu}_e$. We point out here that a good road map includes both our desired destination, but also places that we do not go.

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