Long–Baseline Neutrino Oscillation Experiments

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The status and progress of accelerator long–baseline experiments on neutrino oscillation is discussed. Emphasis is given to the one running experiment in this class, the KEK to Kamioka experiment. Since this example establishes the technique of long–baseline experiments in general, some details of timing and beam aiming are discussed. Preliminary results of this experiment are reviewed. Status of other projects is presented.

1. INTRODUCTION & HISTORY

In the 1950's, the neutrino was discovered with a deector 11m from the Preliminary results of this experiment are reviewed. Status of F One accelerator experiment with a 250 km baseline and mean beam energy around 1 GeV is already running. Others proposed with baselines of 730 km and beams of energy tens of GeV will be up and running in the near future. Very long baseline experiments planned for the more distant future using new accelerator technology are part of the subject of other articles in these proceedings [1] and so are not covered in any detail here. Reactor neutrino experiments have beams of pure $\overline{\nu}_{\rm e}$ at energies of a few MeV, making hundreds of meters a comparably long baseline. Present and future experiments of this type are discussed in detail in other articles in this proceedings.[2]

It is important to realize that these classes of experiment are not competitors searching for the same goal, but rather a complementary set of measurements studying different parts of one theory. The basis change underlying neutrino oscillation can be written:

$$\begin{bmatrix} \nu_{\rm e} \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{pmatrix} \mathcal{M}_{1,{\rm e}} & \mathcal{M}_{2,{\rm e}} & \mathcal{M}_{3,{\rm e}} \\ \mathcal{M}_{1,\mu} & \mathcal{M}_{2,\mu} & \mathcal{M}_{3,\mu} \\ \mathcal{M}_{1,\tau} & \mathcal{M}_{2,\tau} & \mathcal{M}_{3,\tau} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \qquad (1)$$

This matrix can be factored in a way that expresses the different roles of each experiment class. Designing an experiment with parameters that suppress some terms allows a simpler analysis to understand a particular term. Some effective experimental parameters available are mean neutrino energy, detection baseline, beam composition, and whether the experiment is an appearance or disappearance measurement.

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Reactor and solar neutrino experiments with MeV beams of $\overline{\nu}_{\rm e}$ probe one corner of the matrix:

$$\begin{pmatrix} {\rm c}_{12} & {\rm s}_{12} & 0 \\ -{\rm s}_{12} & {\rm c}_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

This generation of accelerator experiments with GeV beams of ν_μ and baselines of $\mathcal{O}(few \cdot 100\,{\rm km})$ probe another:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & {\rm c}_{23} & {\rm s}_{23} \\ 0 & -{\rm s}_{23} & {\rm c}_{23} \end{pmatrix}$$

...and future experiments with longer baselines and mixed ν_μ and $\overline{\nu}_{\rm e}$ beams at tens of GeV will probe the remaining terms including the possible CP phase and matter effects in oscillation:

$$\begin{pmatrix} {\rm c}_{13} & 0 & {\rm s}_{13} \\ 0 & 1 & 0 \\ -{\rm s}_{13} & 0 & {\rm c}_{13} \end{pmatrix} \begin{pmatrix} 1 & {\rm s}_{12} & 0 \\ -{\rm s}_{12} & 1 & 0 \\ 0 & 0 & {\rm e}^{-\imath\delta} \end{pmatrix}$$

2. EXPERIMENTS IN THE FIELD

CERN and FermiLab have proposals for long–baseline experiments with (coincidentally the same) baselines of 730 km and ν_μ beams of tens of GeV. The FermiLab experiment, MINOS [3], is well underway in construction and expected to start data taking in 2003. The CERN proposals focus on two possible detectors, Icarus and OPERA [4], currently under prototype studies. The special emphasis of these detector studies is to be able to search for ν_τ appearance. In Japan, there is a letter of intent for a project associated with the Japan Hadron Facility (JHF) to be located in Tokai, which would use Super–Kamiokande as a far detector giving a baseline of 295 km. The high intensity GeV energy beam would serve to continue the work of K2K in ν_μ disappearance, but also give sufficient statistics to address the possibility of ν_{e} appearance associated with the Θ_{13} mixing matrix elements. This is hoped to start around 2006.

The CERN and FNAL experiments have nearly pure ν_μ beams of a few tens of GeV. The FNAL beamline is under construction as are the new far detector and near detectors for the experiment. CERN has already been testing a prototype focusing horn magnet for the neutrino beamline. Icarus is currently deploying the first 600 ton cryogenic module for testing and atmospheric neutrino data taking. OPERA is approved and now arranging tests of the necessary mechanical support for their proposed detector. The basic technology is emulsion, the efficacy of which is well demonstrated by many earlier experiments. The two difficult tasks are the reading of such a large mass of emulsion, and the automated extraction of "bricks" from modules of the detector for scanning.

At the Soudan mine, the far site for the MINOS experiment, cavity excavation is complete as is most of the above ground supporting infrastructure. Back at FNAL, the beam production site, a prototype detector is being tested and construction on the front detector hall area is well underway. The beamline tunnel should be excavated soon. In general, they report that construction is on schedule to be ready for beam in 2003.

At KEK, the "KEK to Kamioka" (K2K) experiment started taking data for physics runs in June of 1999. Nearly 1/4 of the expected total 10^{20} protons on target have already been delivered and the corresponding neutrino data analysed. This is important since the technical challenges of aiming a neutrino beam precisely and of doing relative time analysis at such great distance with sub-microsecond precision are shown to be manageable. It provides an existence proof of the viability of analyses for itself and for the coming experiments.

3. K2K: The Current Experiment

K2K uses the existing Super–Kamiokande (SK) detector as a far detector for a neutrino beam from KEK, 250 km away. Twenty-eight fully contained neutrino events have been detected in the fiducial volume of SK. The expectation is $37.8^{+3.6}_{-3.8}$, estimated from measurement of neutrino interactions in near detectors and extrapolation using simulation validated by a measurement of the pion kinematics in the decay region. The expected background is $\mathcal{O}(10^{-3})$ events. It is not yet possible to make a conclusive statement regarding neutrino oscillation with the data analysed, but further running will increase the statistics by a factor of four. When all the data are in, oscillation analysis can use spectral information to fully explore the region of $\Delta(m^2) > 3. \times 10^{-3}\mathrm{eV}^2$ for full mixing, or $\sin^2(2\Theta_{23}) \gtrsim 0.6$ for high mass splitting. K2K is strictly a disappearance experiment in the search for $\nu_\mu \to \nu_\tau$ oscillation, but will be sensitive to ν_{e} appearance over a somewhat wider region of parameter space.

3.1. The K2K Neutrino Beam

The primary beam for K2K is 12 GeV kinetic energy protons accelerated by the KEK proton-synchrotron (KEK-PS). Every 2.2 s approximately 6×10^{12} protons in nine bunches are fast-extracted in a single turn, making a 1.1 μs spill. These protons impinge on a 30 mmϕ, 66 cm long aluminum target which is a current carrying element in the first of a pair of horn magnets operated at 250 kA[5]. This design maximizes the efficiency of the toroidal magnetic field to focus positive pions from proton-aluminum collisions while sweeping out negative secondaries. A decay tunnel of 200 m length follows the target area. In fixing this length, a balance must be struck between efficiency for pion decay and contamination of $\overline{\nu}_{\rm e}$ from muon decay.

There are many monitors for the primary and secondary beams. The most important are a gas-Čerenkov monitor which is occasionally moved into the space after the focusing horns to measure pion kinematics, and a stationary segmented ionization chamber downstream of the beam dump to check the beam direction, profile, yeild, and stability on a spill-by-spill basis.

3.2. Neutrino Detection at the Near Site

The near site houses a suite of neutrino detectors with complementary abilities. The detectors sit approximately 300 m from the pion production target (80 m from the beam dump at the end of the decay space) with an intervening berm of approximately 70 m of earth virtually eliminating the chance that any beam products other than neutrinos will be observable. A one kiloton water Čerenkov detector (1kt) uses the same technology and analysis techniques as the far detector, SK. Its 20" photomultiplier tubes (PMTs) and their 70 cm grid spacing are the same as those of SK, giving the same fractional coverage by photocathode, 40%, with 680 PMTs on a cylinder of 8.3 mϕ and 8.6 m height. A muon range detector (MRD)[6], measures the energy, angle, and production point of muons from charged current (CC) ν_μ interactions. It covers $7.6\times 7.6\,m^2$ transverse area with four 10 cm, followed by eight 20 cm, iron plates interleaved with drift chambers. The total mass is 915 tons. The 6632 drift tubes each have $5{\times}7\,{\rm cm}^2$ cross section, and are arranged in horizontal and vertical read-out planes. A scintillating fiber detector (SciFi)[7] with a 6 ton water target has tracking capability, and allows discrimination between different types of interactions such as quasi-elastic or inelastic.

3.3. Aiming & Timing

The crucial elements for the basic operation of a long–baseline experiment are accurate and precise aiming and timing of the beam. For K2K, the beam divergence ($\propto 1/\gamma_\pi$) is enough so that the spectrum and total neutrino flux at the distance of the far detector are roughly constant over a 1 km radius from the axis. Thus, the aiming requirement is that the beam be stably within 4 mr of the survery center. Timing across large distances is now an attainable goal with the availability of information from the Global Positioning System (GPS). K2K has performed a check on the accuracy of the GPS timing by transporting an atomic clock between the two sites for an absolute calibration of any time offset. The result of this test was that the synchronization is correct within the error of the measurement. This error combined with the standard accuracy of GPS signals, 87 ns RMS, gives a total error for site synchronization of < 200 ns. Given the $1.1\,\mu$s full range of the beam spill, a $1.5\,\mu$s search window is sufficient for selection of signal events at the far site. This $\lesssim 10^{-6}$ duty factor reduces the expected background from atmospheric neutrino interactions to a negligible level.

Since there is a magnetic field in and around the target, the aiming of the pion beam is quite sensitive to the alignemnt at which the proton beam. The neutrinos for this experiment come from those pions, as do muons in the same decay process. Therefor, the muons present at the end of the decay tunnel carry information about the neutrino beam. The position center gives the average direction of the neutrino beam, and the yield (normalized to the proton intensity) is a monitor of the proton targetting efficiency. The ionization chamber downstream of the beam dump can detect those muons which penetrate the dump. The shielding of the dump gives it a threshold of 5.5 GeV, so the muons observed are from high energy pions and thus more strongly correlated with the aiming. Figure 1(a) shows the time stability of the centroid of the muon profile for one period in the K2K neutrino runs. The aiming of the neutrino beam is always well within 1 mr of the intended direction. This far surpasses the requirement of 3–4 mr.

The characteristics and stability of the ν_μ beam itself are directly monitored by the MRD using ν_μ interactions with iron. The large area makes it possible to measure the beam direction and width (profile), and the high mass to measure the time stability of the ν_μ event rate, profile and spectrum. For the profile measurement, the starting point of a reconstructed track is regarded as the vertex of the ν_μ-iron interaction. The data re-

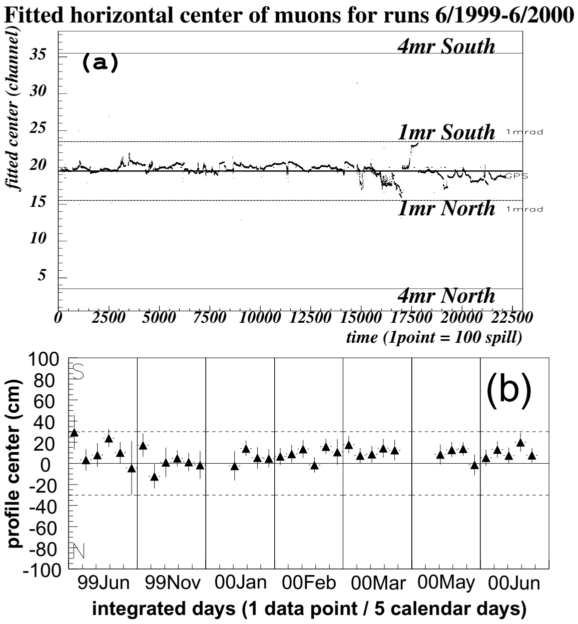

Figure 1. (a) Aiming for high energy muons in the decay space and its time stability. The ordinate is the fitted center of the distribution of muons in the ionization chamber. The abscissa is time; the time unit is hundred beam spills. These data reflect about two months of live time. (b) Aiming stability for the neutrino beam direct measurement. Again, the abscissa is time, but in units of calendar days for the full operating beam time of hte experiment. Each point uses an integrated profile for five days.

duction for the profile measurement requires that tracks be around the time of the beam spill with no muon entering or leaving the detector, and a muon momentum range is selected to assure good acceptance. Tracks with a common vertex are taken as a single event with the longest track assumed to be a muon. The vertex distribution is corrected for geometrical acceptance to obtain the beam profile. Figure 1(b) shows the time distribution of fitted neutrino beam center throughout the data analysed. This measurement supports the indirect measurement from the beam-dump ionization chamber.

3.4. Extrapolation to the Far Detector

Comparison between expected and observed numbers of ν_μ events at the far site is done with this knowledge of measured beam stability. To predict the ν_μ beam characteristics at the far site, a normalization measurement at the near site and the extrapolation of the information from near to far are necessary. For the rate normalization, the 1kt is used so that any detector or analysis bias is suppressed. For the extrapolation, once the kinematic distribution of pions after production and focusing is known it is possible to predict the ν_μ spectrum at any distance from the source.

A gas-Čerenkov detector has been placed in the target area of the beamline to measure the pion $(|\vec{\mathrm{P}}|, \theta)$ distribution. (During normal neutrino data-taking this detector is retracted from the beamline to minimize the material in the path of the pions.) Čerenkovphotons generated by pions in the detector are focused by a spherical mirror to an array of custom PMTs of 8 mm effective diameter in its focal plane. Photons emitted by particles with the same velocity and incident angle with respect to the mirror arrive at the same position in the focal plane. Since this is independent of photon incident position with respect to the mirror, the pion kinematics can be fit using the measured light intensity distributions. Measurements are made at various indices of refraction, controlled by gas pressure to allow analysis of the velocity distribution of pions. Data are taken with a pion threshold of 2 GeV to avoid background from the 12 GeV primary protons. Figure 2 shows the measured ν_μ energy spectral shape at near site and far to near ν_μ flux ratio along with the beam simulation result. This simulation is based on GEANT[8] with detailed description of materials and magnetic fields in the target and decay region. It uses as input a measurement of the primary beam profile at the target. Primary proton interactions on aluminum are modeled with a parameterization of hadron production data[9]. Other hadronic interactions are treated by GEANT-CALOR[10]. The PIMON measurement is well reproduced by the beam simulation.

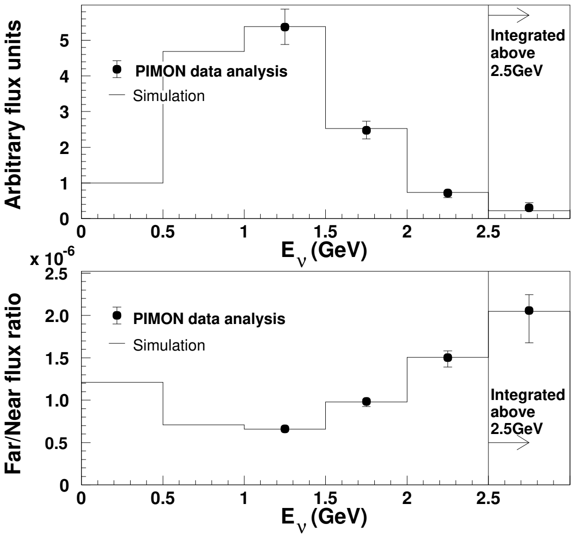

Figure 2. PIMON data analysis: (top) The ν_μ energy spectral shape at the near site from the measurement with beam simulation results overlaid. Normalization is done by area above 1 GeV. (bottom) Far to near ν_μ flux ratio from the measurement with beam simulation results overlaid. The vertical error bars for the PIMON data analysis reflect the total uncertainty.

3.5. Events at the Far Detector

Initial data selection at the far detector is made with the same analysis methods and tools as used in atmospheric analyses for SK. The main difference is the timing selection. Final selection is made by comparing two Universal Time Coordinated (UTC) time stamps from the GPS system, T_{KEK} for the KEK-PS beam spill time and T_{SK} for the SK trigger time. The time difference between two UTC time stamps, $\Delta(T) \equiv T_{\mathrm{SK}} - T_{\mathrm{KEK}} - TOF$ where TOF is the time of flight of a neutrino, should distribute around 0 to 1.1 μs to match the width of the beam spill of the KEK-PS. Since the measured limit on synchronization accuracy for the two sites is < 200 ns, beam-induced events are selected in a 1.5 μs gate. Figure 3 shows the distribution of relative timing between SK events and the expected beam arrival time for various stages of reduction.

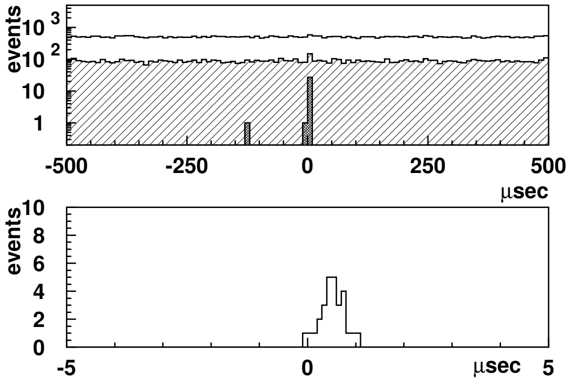

Figure 3. $\Delta(T)$ distribution for various stages of data reduction. The wide time window in the top plot shows the character of the background. After all selection except timing, there is one event (presumably a good atmospheric neutrino event) in the 1 ms window but out of the 1.5 μs selection window. Near the time of the beam spill (bottom plot) the signal is clear with negligible background.

3.6. Preliminary Results

[2] In the 22.5 kton fiducial volume, 28 fully contained events have been observed in time with the KEK-PS beam spill. The expectation estimated using the 1kt detector at the near site for normalization of the beam monte carlo is $37.8^{+3.6}_{-3.8}$. The expected number of events for analyses of CC interactions in the other near detectors are $41.0^{+7.0}_{-7.4}$ for MRD (iron target) and $37.2^{+7.3}_{-7.6}$ for SciFi (water target), confirming the 1kt prediction within the large uncertainty. With this level of statistics it is still impossible to conclude anything about whether the measurement is consistent with the oscillation hypothesis as suggested by atmospheric observations. One can only say now that the observation is inconsistent with the hypothesis of no oscillation or other new physics

[2] These results are updated since the conference.

at the 90% level. This is calculated by integrating the "lower tail" probability for observation of $\mathrm{N}_{\mathcal{O}} = 28$ events over a distribution of expectations derived from the central value and the known error.[3] That is:

$$\mathrm{C.L.} \equiv 1 - \int_0^{\infty} \left(\mathrm{e}^{-\lambda} \sum_{i=0}^{\mathrm{N}_{\mathcal{O}}} \frac{\lambda^i}{i!} \right) \times \mathcal{P}(\lambda) \mathrm{d}\lambda$$

where $\mathcal{P}(\lambda)$ is the differential probability distribution for the expectation, in this case taken as a gaussian shape on each side of the central value. Of course, as a practical matter this expression is integrated numerically over a finite range.

At the conclusion of K2K, with four times as much data, a meaningful statement about neutrino oscillation will be possible. Using single ring muon like events (which are largely from quasi-elastic interactions) a neutrino momentum spectrum can be measured and a binned analysis done. For reference, figure 4 shows the current state of spectral analysis at the far detector.

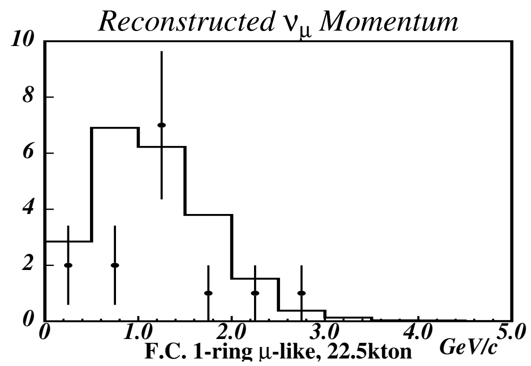

Figure 4. The reconstructed neutrino momentum of single ring μ-like events in the fiducial volume of SK in time with the K2K beam. The points are data with statistical errors shown, and the histogram is the prediction of monte carlo with normalization set by the 1kt measurement.

[3] One can argue about whether the lower tail or the "two-sided" distribution should be integrated. Each method has its advantage. This is the motivation for being as explicit as possible about the method used here.

4. CONCLUSION

The field of accelerator long–baseline neutrino physics is presently very active and holds promise for a productive future in the next decade. By the conclusion of K2K, we may have a definitive answer to whether the atmospheric neutrino results are caused by oscillation or other new physics. The next experiments in this vein, MINOS and the CERN-Gran Sasso experiments, should measure the mixing of ν_μ and ν_τ precisely in a controlled setting. While there is some possibility that the Θ_{13} mixing matrix element may be measurable at these experiments, in any event they should refine the parameter space for future searches at a neutrino factory.

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