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for
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Cosmic Rays and Elementary Particles
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Research Program in Neutrino Physics, Cosmic Rays and Elementary Particles

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1.1 Introduction

At the time of the last renewal, we were just finishing the scheduled detector maintenance and beginning to fill with water. The accident on November 12, 2001, which destroyed 6,777 inner detector PMT’s and 1,160 outer detector PMT’s has set back our experimental schedule by about one year. The collaboration has spent the intervening months in the process of recovery. This includes the accident investigation, the detector clean-up and the PMT re-arrangement and replacement. The timely support from the DoE has allowed us to replace the damaged outer detector tubes. The inner detector tubes are now outfitted with a covering shell which prevents a repetition of the accident. At the time of this writing, we have finished the tube installation and will begin re-filling the detector with water October 4. This will allow us to be up and ready when the KEK neutrino beam re-starts in January.

In the midst of our rebuilding, the past year has nevertheless seen a number of beautiful results come out of the Super–Kamiokande solar neutrino analysis. Having accumulated what is by far the world’s largest sample of solar neutrino events, these high-statistics, precision data have allowed us, in the last year alone, to publish three refereed journal articles on topics ranging from solar neutrino oscillations to gamma-ray bursts to relic supernova neutrinos.

Echoing the now famous discovery of large atmospheric neutrino mixing in 1998, in 2002 large solar neutrino mixing was uniquely determined by using Super–K data alone. In combination with other experiments’ data, the LMA region has been conclusively selected at better than the 95% confidence level. Oscillations into purely sterile neutrinos are now looking so unlikely everywhere in phase space that the possibility can be all but disregarded.

Although Super–Kamiokande has taken data for about five years, many of its solar neutrino precision measurements are still limited by statistical uncertainty and will therefore be improved by taking more data. In other cases, continued study of sources of systematic errors will prove decisive in yielding more physics results in the months and years to come. The near future promises yet more stimulating developments, as various UCI in-house projects, including a reworked Super–K–II Intelligent Trigger, a revamped depth-dependent Monte Carlo, an improved understanding (and reduction) of our backgrounds, an enhanced oscillation analysis, an enriched extraction of relic supernova neutrino signals, and a search for a non-zero neutrino magnetic moment.
Super-Kamiokande’s studies of atmospheric neutrinos have provided the most credible evidence for neutrino oscillation and neutrino mass. The significant experimental characteristics that made this possible are: (a) a wide range of neutrino energies, from 100 MeV to 1000 GeV; (b) a large variation in baselines, from 10 km to 10000 km; (c) a well-predicted initial ratio of electron and muon flavor neutrinos; (d) excellent particle identification in the detector; (e) up-down symmetry in the detector; (f) good energy and directional resolution; and (g) large data samples, with nearly 13,000 total atmospheric neutrinos analyzed. Exploiting these advantages, the data are finely binned in energy and angle during fitting, resulting in a precise estimate of the oscillation parameters. These same data can exclude alternate hypotheses such as neutrino decay and exotic oscillation processes with a high level of confidence. Particularly important are recent studies that exclude pure oscillation between muon neutrinos and sterile neutrinos, and limit the allowable admixture of sterile neutrinos to a relatively small fraction of the effect.

Additional exposure to the atmospheric beam will confirm and extend these measurements. The determination of oscillation parameters is now limited by systematic uncertainties. With further data from Super–Kamiokande and the near detectors at K2K, these systematics can be improved.

The K2K experiment started in June 1999 and the first neutrino event was observed on June 19th, 1999. Since then we have taken data corresponding to 235 days of running. This is about half of the planned amount of data of the K2K experiment. Currently the SK detector is being rebuilt and the K2K experiment is planned to restart at the end of December 2002. In this report we present the results of an analysis based on 235 days of data taken up to 2001. We see 56 neutrino events when we would have expected about 80. The number and observed spectrum is consistent with the $\Delta m^2$ region observed with atmospheric neutrinos.

We are also doing neutrino physics with the near detectors at KEK and have results on $\pi^0$ production and proton decay backgrounds.
1.2 Super-Kamiokande Reconstruction

The implosion event of November 11 left the detector severely damaged. A study was begun immediately to identify the cause of the implosion and an engineering program was initiated to develop measures to prevent a reoccurrence. These programs are discussed in other sections of this report.

Work also began immediately on planning and implementing the detector’s reconstruction. The rebuilding of the Outer Detector (OD) and the Inner Detector (ID) were carried out in parallel and synchronous efforts. This section deals mainly with the reconstruction of the OD, which is the responsibility of the US groups. UCI was the coordinating institution for the OD reconstruction.

1.2.1 Outer detector damage assessment

Preliminary damage estimates were done in November and December 2001. Techniques employed included visual inspections with a small robotic underwater camera, and electrical testing of the photomultipliers (PMTs).

The results showed widespread damage to the PMTs, the waveshifter plates, and the Tyvek that isolated the inner and outer detectors. All areas of the detector that were more than a few meter below the water’s surface were affected. As expected, the severity of the damage increased with water depth.

Additionally, the shaking associated with the implosion broke many of the PVC bolts that secured the older IMB PMTs to the support structure. This resulted in additional damage to the tubes as the water was drained from the tank.

An accurate quantitative damage assessment was made as the water was pumped from the detector in February and March of 2002. The results follow:

- 1027 OD PMTs (of 1885) were destroyed, mostly through destruction of the tube’s glass envelope. In many cases it appears that the tube was simply forced into the watertight PVC pipe structure attached to the tube to house the divider chain. The pressure inside the PVC pipe was one atmosphere. The pressure wave generated in the detector was also of sufficient intensity to destroy many of the PVC pipes themselves. The newer tubes (with potted base divider chains) that were installed
last summer as part of the upgrade largely survived the blast. This same design is used in the new tubes purchased for the reconstruction.

- An additional 40 tubes that survived the blast intact were unusable due to cable jacket damage that allowed water to seep into the cable. A small number of additional tubes were damaged or died of other causes since the upgrade in 2001, resulting in the need to purchase a total of 1050 new 8 inch PMTs from Hamamatsu. (The difference between the number of purchased tubes and the number destroyed was made up by spares on hand from the upgrade.)

- There are still some 500 IMB tubes in use in the detector, mainly on the top and in the upper few layers of the barrel. These survived because they were on or near the top of the detector and so were out of the water or within a few meters of the surface when the implosion took place.

- 247 Waveshifter plates (of 1885) were destroyed. Many were badly cracked while others were shattered.

- About two thirds of the wall Tyvek and the entire bottom Tyvek layer was destroyed. Replacement of the ID tubes required removal of the remaining (undamaged) Tyvek, effectively destroying it as well; All Tyvek thus required replacement.

- The reflective Tyvek used on the extreme outer walls of the detector was also damaged and except for the undamaged top layer was replaced.

### 1.2.2 New Tube Installation

The new tubes are connected to the existing cables by splicing. SHV connectors and a double layer of heat shrink tubing are used. The splice was extensively tested at UCI in a pressure vessel and also in situ after the upgrade.

A decision not to replace all cables was made early in the reconstruction planning; It would have been yet another major undertaking to replace all of the thousand or more kilometers of cable. The turbulence in the water, and the debris cascading through the water during the implosion event however damaged many of the cable jackets. Likewise the draining of the detector tank
and the removal of the damaged PMTs lead to additional cable damage. The
cable used in the OD is especially susceptible to failure should water enter
the cable near a splice point; hence the decision was made to replace all of
the cable (for new tubes) that was below the water level when the implosion
took place. Hence all barrel and bottom cables were spliced at the extreme
upper levels of the barrel. The new tubes were supplied with sufficient cable
to allow splicing near the top of the detector.

Splicing the cables high on the detector wall was done using gondolas
suspected from a circular track at the top of the detector’s cylindrical wall.

1.2.3 Reconstruction

The accompanying chart exhibits the main phases of the reconstruction with
emphasis on the OD activities.

The chart shows some of the preliminary work done in preparation for the
detector reconstruction, including the implosion tests of the 50 cm ID tubes,
and the detector demolition during which the debris from the implosion was
removed and the detector cleaned.

The chart also shows the three phases of the detector reconstruction de-
fined by the geometry of the cylindrical detector:

- Top Reconstruction: There was no damage to the top layer of PMTs
due the actual implosion. However a number of ID and OD tubes had
to be removed to allow access to the ID. At the same time several failed
OD tubes were replaced. In the case of the ID, all tubes were removed
and reinstalled at half density.

- Barrel Reconstruction: The OD barrel reconstruction was made from
a donut shaped floating floor circling the entire outer PMT support
structure. This allowed a safe and convenient access to the PMTs as
the water level in the tank was lowered in a controlled fashion. As noted
above, the splices were made near the top of the barrel; two gondolas
that moved horizontally as well as up and down were employed. The
new cables were deployed and the old cables were removed via the
gondolas. The Tyvek was installed from the floating floor as the tubes
were spliced.

- Bottom Reconstruction: The bottom tubes and Tyvek were installed
after the water was fully removed from the tank. The process was
similar to that for the barrel, employing the same gondolas. In addition to the bottom PMT work is the installation of the floor and outer wall Tyvek.

As of 21 September, the top and the barrel have been refitted with tubes, waveshifters, and new Tyvek. The bottom work is approximately half completed. The outer wall Tyveking has started and will take about another week. The final 4 days effort will be the installation of the floor Tyvek.

All major components for the reconstruction are installed or are in hand. It is anticipated that the bottom reconstruction will be completed on schedule by 5 October, at which time filling of the detector will commence. When the water level reaches within 1.5 meters of the top layer of PMTs (around mid-December), several weeks of effort will be required to complete the rebuilding of this PMT layer and to close the openings made to access the ID for the reconstruction activities. Full operation is expected in early January 2003.

The detector reconstruction was a long and labor-intensive operation, starting in early March and continuing through early October. The work required an almost continuous presence of a large contingent of US researchers and students. As many as 22 workers were on site during parts of the reconstruction effort. Approximately 330 man-weeks of on-site effort were required. An additional 10 man-weeks will be needed to seal the Outer detector. The corresponding effort of our Japanese colleges working on the inner detector was much greater.

A major portion of the labor force consisted of undergraduate students and High School Teachers supplied largely by UCI, SUNY, the University of Minnesota (Duluth), and the University of Washington. A total of 27 undergraduate students and High School teachers were employed for periods of 2 weeks to 3 months.

1.2.4 Results

Electrical tests of the old and newly installed tubes show (to date) that they are operating correctly. Two shorted PMTs (of 1275) on the barrel were not replaced. These had water in the cables, apparently due to cable damage high in the detector. This damage presumably was not associated with the implosion event.

Data taking will commence in early October as the detector is being filled. After a few weeks Super-K will again be the largest operational supernova...
The replacement of over 1000 of the old IMB tubes brings the OD to an operational level not achieved even in its original configuration. It is likely that only a few of the 1885 channels will be non-operational. At the start of data taking for SK-1 we had already lost 81 of the IMB tubes and tubes were continuing to fail at a rate of about 1 per week. The detector currently has some 500 of the old tubes, originally purchased in 1985. The tubes themselves are largely sound but the technology used to isolate the base electronics from the detector water is a failure point in their design. These tubes should be replaced by the current generation of faster tubes employing the latest in base potting techniques. This could be done in 2005 when the ID is scheduled to be brought back to its original PMT density for use with the JHF neutrino beam. At today’s prices, the cost to replace the IMB tubes would be well under 1 million dollars.
1.3 NUCLEON DECAY AND ATMOSPHERIC NEUTRINOS

1.3.1 Nucleon Decay

Status and motivation

The Super–Kamiokande search for nucleon decay has not yielded any positive evidence, but the absence of nucleon decay, now extended into the decade between $10^{33}$ to $10^{34}$ years lifetime, has provided stringent constraints that must be addressed by any proposed Grand Unified Theory. In most GUT’s, nucleon decay rates are naively predicted to be too large compared to our observational experience and some mechanism must be contrived to reduce them. The simplest theories, such as SU(5) and minimal SUSY SU(5) predict such short lifetimes that the they are already excluded (the two just mentioned, by IMB/Kamiokande and Super–Kamiokande respectively). Certain new theories have included features that make the lifetime arbitrarily long, for example separating quarks and leptons by extra spatial dimensions[1, 2]. Other theories involving extra-dimensions predict surprising new modes [11]. However, a large number of current GUT’s that allow a finite nucleon lifetime predict decay rates not much beyond current limits[12, 13, 14]. Clearly the search for nucleon decay remains an extremely valuable discriminating experiment for understanding the fundamental nature of particles and forces.

Figure 1.1 shows selected nucleon lifetime limits compared to ranges of expectations from a variety of Grand Unified Theories[15, 16, 17, 18, 19, 20, 21, 22]. Further running of Super–Kamiokande is motivated by an expected doubling of the present nucleon decay sensitivity. While this additional sensitivity is not sufficient to exclude any of the theories listed, the additional exposure is probing and constraining these theories. Given the numerous predictions that the finite nucleon lifetime may truly lie in this range, one can consider several possible outcomes from continued exposure. First, if a “golden” event or two is seen, then the approximate scale of the nucleon lifetime has been found, which can securely motivate the size of any next-generation detector. More importantly, whether the final state particles make energetic electromagnetic showers, as in the $e^+\pi^0$, or involve charged kaons, as in $\pi K^+$, is a decisive question in the choice of the technology most suitable for any next generation detector. Simply observing nucleon decay will provide strong validation of the idea of Grand Unified Theories, and simply knowing
Figure 1.1: Selected experimental limits on nucleon lifetime compared to the ranges predicted by a variety of Grand Unified Theories. The hollow oval indicates the expected limit from doubling the current Super–Kamiokande exposure.

the dominant branching mode is a significant discriminant between the wide variety of GUT’s under consideration. Conversely, the non-observation of nucleon decay will further constrain the set of valid models, giving weight to those that allow for very long lifetimes, and casting doubt on those that require shorter lifetimes.

Super-Kamiokande I limits

Although new analyses have been delayed by the need to repair the detector, proton-decay limits for several key modes have been updated using the full Super-Kamiokande I dataset: 1489 live-days, or 91.7 kton-yrs. The benchmark $p \rightarrow e^+\pi^0$ mode remains nearly background-free, with 0.2 events expected and no candidates observed (see Figure 1.2). The 90% confidence level limit for this mode is $\tau/\beta > 5.7 \times 10^{33}$ yr. For $p \rightarrow \mu\pi^0$, the Super-Kamiokande I limit is $\tau/\beta > 4.2 \times 10^{33}$ yr.

Improvements to the $p \rightarrow \nu K^+$ mode have eliminated two sources of pathological background, one involving the low-energy de-excitation tag, and the other affecting the $K^+ \rightarrow \mu^+\nu$ channel. For the former, the efficiency (including $K^+$ branching ratio) is 8.7%, with 0.3 expected background and no candidates; for the latter, the efficiency is 6.5% with 0.9 expected background.
Figure 1.2: Simulated $p \rightarrow e^+ \pi^0$ data (left), simulated atmospheric neutrino background (center) and 91.7 kton-yr Super-Kamiokande I data (right). The efficiency is 43%, while the expected background for the present exposure is 0.2 events and no candidates are observed.

and no candidates. Combining these two analyses with the independent muon spectral fit gives an overall limit $\tau/\beta > 2.0 \times 10^{33}$ yrs.

**Super-Kamiokande II sensitivity**

Since proton decay signatures yield fully-contained visible energy from 0.1 to 1 GeV, we anticipate that running the Super–Kamiokande inner detector with half of the original PMT coverage will be worthwhile. This will be 20% photocathode coverage, identical to Kamiokande and 4 times IMB, both of which were quite successful. Because of the large dimensions of the detector, 30 meters across inside, we profit not only from the fiducial mass of the detector, but also by projecting the Cherenkov rings over a wide area, thereby well separating them on the photosensor surface. The search for $p \rightarrow e^+ \pi^0$ will be practically unaffected. The most significant impact of fewer PMT’s, and one which is still under study, is that faint rings due to asymmetric $\pi^0$ decay, barely-above-threshold charged pions, and 6 MeV nuclear de-excitation, will become more difficult to detect.

An example of this is shown in Figure 1.3, which compares the same Monte Carlo event of $p \rightarrow \bar{\nu}K^+$ under two configurations of inner detector PMT’s. The left panel shows the original configuration of 11146 photomultiplier tubes, and the right panel shows the new configuration with only half that number. The collapsed ring from the 236 MeV/c muon is sharp in both cases, and the Cherenkov angle of 35° should be readily reconstructed from the 2 nanosecond timing of the PMT’s. To distinguish these events from
Figure 1.3: A comparison of the same Monte Carlo event of $p \to \nu K^+$ with $K^+ \to \mu^+ \nu_\mu$ and de-excitation of $^{15}N^*$ to a 6 MeV gamma ray. The left panel shows the original configuration of 11146 photomultiplier tubes, and the right panel shows the new configuration with half that number. The gamma tag precedes the decay $K^+ \to \mu^+ \nu_\mu$ by 20 nanoseconds, as seen in the histograms of PMT hit times. The outer detector, in the upper corner of each event display, shows mostly out-of-time dark noise hits in a wider time window.

the copious background of atmospheric $\nu_\mu$ interactions, we search for the de-excitation of $^{15}N^*$ by a 6 MeV gamma ray[23, 24].

This gamma tag is possible because the $K^+$ is emitted below Cherenkov threshold, stops 15 cm away from the proton decay vertex, and decays with a mean lifetime of 12 ns. Therefore the prompt de-excitation of $^{15}N^*$ precedes the visible kaon decay by a time interval that can be resolved by the Super–Kamiokande detector. The signature is unique to proton decay when 8 or more hits are required in a sliding window 12 ns wide.\footnote{It is important to note that this analysis does not rely on the 6 MeV gamma ray \textit{triggering} the detector; the delayed muon from kaon decay at rest produces ample light to trigger with 100% efficiency. Hence trigger threshold considerations with reduced photocathode coverage are unimportant here.} Figure 1.4 shows
1.3. NUCLEON DECAY AND ATMOSPHERIC NEUTRINOS

the number of hits found in the sliding window, considering proton decay Monte Carlo, atmospheric neutrino background Monte Carlo, and 1289 days of data. The signature from the gamma tag is expected to be between 8 and 60 hits (with the full complement of PMT’s), with an efficiency x branching ratio of 8.8%. The background expected from atmospheric neutrinos is 0.5 events for the 1289-day sample. The lifetime limit for this method alone is \( \tau/\beta > 10^{33} \text{ years} \) (a preliminary result, updated from Ref. [24]); the combined limit including other channels now stands at \( 2 \times 10^{33} \text{ years} \). It is expected that the efficiency, and perhaps the background, will be somewhat worse with half of the inner PMT’s, but the signal stands out from the cut by tens of PMT hits, so we are confident that this analysis will continue to be effective. A detailed estimate of the new efficiency requires re-simulating the Monte Carlo samples, re-optimizing the vertex fitting algorithm and retuning the cuts.

\( n\bar{n} \) oscillation

A recent paper has argued[3] that the \( \Delta B = -2 \) process of \( n\bar{n} \) oscillation is a generic prediction of a large class of supersymmetric Grand Unified Theories with spontaneously-broken \( B-L \) symmetry. In the case of supersymmetric unification based on the gauge group \( SU(2)_L \times SU(2)_R \times SU(4)_c \), the \( n\bar{n} \) lifetime is closely related to the neutrino masses via the See-Saw mechanism. Based on the inferred value of the largest neutrino mass from atmospheric oscillation data, the upper bound on the \( n\bar{n} \) lifetime in such models appears to be \( 10^9 - 10^{10} \text{ seconds} \). Other models which propose new spacetime dimensions to explain neutrino oscillation also predict \( n\bar{n} \) oscillation.[4]

Searches for \( n\bar{n} \) oscillation in nuclei rely on the identifying the subsequent \( N - \pi \) annihilation products. In addition to final-state nuclear interactions of these secondaries, the rate of bound \( n\bar{n} \) oscillation is strongly suppressed due to the nuclear potential well. The free \( n\bar{n} \) lifetime of theoretical interest, \( \tau_{n\bar{n}} \), is related to the corresponding lifetime in a nucleus \( A \) by the relation \( \tau_A = (\tau_{n\bar{n}})^2 T_A \), where \( T_A \) is a suppression factor which can be calculated in a quantum mechanical potential model, or by a quantum field approach. A recent calculation finds, for \(^{16}\text{O} \), \( T_{^{16}\text{O}} = 1.2 \text{ fm}^{-1} \), or equivalently, \( T_{^{16}\text{O}} = 3.6 \times 10^{23} \text{ sec}^{-1} \).[5] For comparison, the older calculation of Dover, et al., predicts (more optimistically) \( T_{^{16}\text{O}} = 1 \times 10^{23} \text{ sec}^{-1} \).[6] Adopting the more conservative value of \( T_{^{16}\text{O}} \), the bound \( n\bar{n} \) lifetime \( \tau_{n\bar{n}} \) corresponds to a free
Figure 1.4: The distribution of early PMT hit times in a 12 ns sliding window that precedes the PMT hit times corresponding to the muon ring. The dashed curve shows that between 8 to 60 extra hits may be expected from the prompt gamma due to nuclear de-excitation during proton decay within $^{16}$O. The solid curve shows that our atmospheric neutrino Monte Carlo predicts most neutrino events produce less than 8 hits for this algorithm. The data from the fully-analyzed 1289-day exposure are overlayed.

$n\pi$ lifetime $\tau_{n\pi}$:

$$\tau_{n\pi}/(10^8 \text{ sec}) = 0.93 \sqrt{\tau_{^{16}O}/(10^{32} \text{ yr})}.$$

Using an empirical model of the $N - \pi$ annihilation products, the Kamio-
kande experiment set the limit $\tau_{^{16}O} > 4.3 \times 10^{31} \text{ yr}$ (90% confidence level).[7] This analysis quoted an efficiency of 33% with an expected background rate of 1.0 (kton-yr)$^{-1}$. Assuming $T_{^{16}O} = 3.6 \times 10^{23} \text{ sec}^{-1}$, the Kamiokande measurement translates into a limit on the free $n\pi$ lifetime $\tau_{n\pi} > 6 \times 10^7 \text{ sec}$, only slightly worse than the best limit from reactor-based searches: $\tau_{n\pi} > 8.6 \times 10^7 \text{ sec}$. The Fréjus[9] and Soudan–II[10] experiments have also set limits comparable to, or slightly better than, the Kamiokande result.
A preliminary, as-yet unpublished, search for $n\pi$ oscillation in Super-Kamiokande has yielded no evidence of a signal, and improves the Kamiokande limit on $\tau_{\pi O}$ by approximately an order of magnitude. This in turn implies a factor $\sim 3$ improvement in Kamiokande’s free $n\pi$ lifetime limit.\textsuperscript{2} Thus the result, when sufficiently mature for publication, should be the world’s best, even after assuming the most pessimistic bound-neutron suppression factor found in the literature. For a ten-year Super-Kamiokande run (assuming, conservatively, the Kamiokande efficiency and background level) we can expect a 90\% confidence level sensitivity $\tau_{\pi O} \sim 10^{33}\text{yr}$, equivalent to $\tau_{n\pi} \sim 3 \times 10^8\text{sec}$; a factor 3.5 improvement on the best reactor limit. Since this analysis is background limited, beam data from the 1-kton near-detector at KEK will be invaluable in reducing the systematic uncertainty of the background subtraction.

### 1.3.2 Atmospheric Neutrinos

Super-Kamiokande’s studies of atmospheric neutrinos have provided the most credible evidence for neutrino oscillation and neutrino mass. The significant experimental characteristics that made this possible are: (a) a wide range of neutrino energies, from 100 MeV to 1000 GeV; (b) a large variation in baselines, from 10 km to 10000 km; (c) a well-predicted initial ratio of electron and muon flavor neutrinos; (d) excellent particle identification in the detector; (e) up-down symmetry in the detector; (f) good energy and directional resolution; and (g) large data samples, with nearly 13,000 total atmospheric neutrinos analyzed. Exploiting these advantages, the data are finely binned in energy and angle during fitting, resulting in a precise estimate of the oscillation parameters. These same data can exclude alternate hypotheses such as neutrino decay and exotic oscillation processes with a high level of confidence. Particularly important are recent studies that exclude pure oscillation between muon neutrinos and sterile neutrinos, and limit the allowable admixture of sterile neutrinos to a relatively small fraction of the effect.

The allowed region for two-component $\nu_\mu \rightarrow \nu_\tau$ oscillation is shown in Figure 1.5. The best fit ($\sin^2 2\theta, \Delta m^2$) point lies barely outside the physical region at $(1.03, 2.5 \times 10^{-3}\text{eV}^2)$, with $\chi^2 = 162.7/170$. The best fit inside

\textsuperscript{2}The analysis in [7] assumed the value $T_{\pi O} = 10^{23}\text{sec}^{-1}$, and quoted the free lifetime limit $\tau_{n\pi} > 1.2 \times 10^8\text{sec}$ (90\% confidence level). If this $T_{\pi O}$ value is adopted, the $\tau_{n\pi}$ sensitivity of a 10-year Super-Kamiokande run would be $\sim 6 \times 10^8\text{sec}$. 

Figure 1.5: Combined oscillation limits from the full Super-Kamiokande I data-set (left), with single-ring contained data (center) and multi-ring/upward-muon data (right). The predictions without oscillation and at the best-fit point are superimposed.

the physical region at $(1.00, 2.5 \times 10^{-3} \text{eV}^2)$ is nearly indistinguishable ($\chi^2 = 163.2/170$). At 90% confidence level, $\sin^2 2\theta > 0.92$ and $1.6 \times 10^{-3} < \Delta m^2 < 3.9 \times 10^{-3} \text{eV}^2$. The no-oscillation hypothesis gives an extremely description of the data ($\chi^2 = 456.5/172$).

While limits on 3-neutrino oscillation involving $\sin^2 2\theta_{13}$ remain uncompetitive with those from CHOOZ, previous limits on pure $\nu_\mu \rightarrow \nu_\tau$ have been extended to encompass an admixture $\nu_\mu \rightarrow (\cos \xi \nu_\tau + \sin \xi \nu_\mu)$. For pure $\nu_\mu \rightarrow \nu_\tau$ oscillation $\sin \xi = 0$, and the 90% confidence level on such an admixture is $\sin^2 \xi < 0.2$.

Additional exposure to the atmospheric beam will confirm and extend these measurements. The determination of oscillation parameters is now limited by systematic uncertainties. With further data from Super–Kamiokande and the near detectors at K2K, these systematics can be improved. However, other atmospheric neutrino studies discussed below are limited by the present statistics, and are crucial to establishing the detailed nature of neutrino oscillation.

We are confident that atmospheric neutrino studies can continue unimpaired with 50% of the inner detector PMT’s. The 20% photocathode cover-
age is identical to Kamiokande, but Super–Kamiokande benefits from its large scale (which distributes Cherenkov rings over more pixels) and $20\times$ greater fiducial mass. Energy resolution will degrade by about 1%, while position and direction resolution should be nearly unchanged. Particle misidentification between electron showers and muon tracks should be no worse than 2% as in Kamiokande (compared to 0.5–1% in Super–Kamiokande). The effects on multi-ring identification are still under study; however the relevant algorithms were under active development and improvement before the incident.

$\nu_\tau$ appearance search

Analyses to identify a sample of charged-current $\nu_\tau$ interactions are in progress and preliminary results have been reported at conferences,\cite{26} Due to the complicated decay modes of the tau, as well as the large hadronic recoil multiplicity, it is not possible to isolate a very pure signal from the atmospheric neutrino beam, which extends to high energy, contains a large electron neutrino component, and includes the usual fraction of neutral-current interactions. Nevertheless, for the oscillation parameters implied by $\nu_\mu$ disappearance measurements (maximal mixing and $\Delta m^2 = 3 \times 10^{-3} \text{eV}^2$), only upward-going neutrinos have sufficient energy for tau production ($E_{\text{min}} \sim 3.5 \text{GeV}$), as well as sufficiently long baseline for oscillation. Therefore, these analyses aim to create a sample enriched with charged-current $\nu_\tau$ interactions and search for an excess in the upward direction.

To enhance the tau fraction, neural network and likelihood techniques based on visible energy, and the geometry of energy flow are under development. Since the $\nu_\tau$ signatures are too complicated to reconstruct in detail even with the full 40% photocathode coverage, these techniques rely on a more global analysis of the light distribution and should be largely insensitive to any loss of ring-finding efficiency with reduced photocathode coverage. Assuming the measured oscillation parameters are correct and the atmospheric neutrino Monte Carlo accurately models the variety of neutrino interactions, an excess of $\nu_\tau$-enhanced events is observed in the upward direction. The current result is $92 \pm 35^{+15}_{-23}$ excess $\nu_\tau$ events, where the first error is a statistical uncertainty from the fit, and the second is a systematic uncertainty due to the oscillation parameters: the allowed range of $\Delta m^2$ and the possible admixture of 8.7% $\nu_e$ as allowed by CHOOZ under a 3-flavor oscillation scenario. Doubling the statistics with further exposure should im-
Figure 1.6: Zenith angle distribution of atmospheric neutrino events selected by a neural net analysis tuned to enhance the fraction of charged current $\nu_\tau$ interactions. The plot shows the result expected after doubling the current 3.5 years of Super-Kamiokande exposure. The data points represent the number of events detected; the lower histogram represents the Monte Carlo prediction without accounting for $\nu_\tau$ appearance; the filled histogram represents the expected additional events due to $\nu_\tau$ appearance with the best fit oscillation parameters of $\sin^2 2\theta = 1$ and $\Delta m^2 = .003$ eV$^2$.

prove the result to $184 \pm 50$; even assuming no further reduction in systematic uncertainty, this represents a $2.7\sigma$ effect. Figure 1.6 shows the result for this hypothetical doubling of statistics from further running.

Search for the oscillation pattern

Although the global fit of all atmospheric neutrino data prefers nearly maximal $\nu_\mu \leftrightarrow \nu_\tau$ oscillation, the sin-squared form demanded by quantum mechanics has not yet been directly observed. Preliminary studies are attempting to
isolate a subsample of the data with sufficient $L/E$ resolution to exhibit this effect. Figure 1.7 shows one simulated data set reflecting the present four-year exposure (the actual data is kept in reserve until the analysis is fully developed). Observation of the first oscillation minimum will be statistically enhanced with doubled statistics.

References


1.3. NUCLEON DECAY AND ATMOSPHERIC NEUTRINOS

N. Sakai and T. Yanagida, Nucl. Phys. B197 83 (1982);


1.4 Solar Neutrinos at Super–Kamiokande

1.4.1 Introduction

The past year has primarily been one of rebuilding for the Super–Kamiokande Collaboration. Nevertheless, our low-energy analyses, which now encompass the entire solar neutrino data set for Super–K–I, have continued apace.

These neutrinos are produced by this nuclear reaction in the Sun:

\[ {}^8B \rightarrow {}^8Be^* + e^+ + \nu_e \]  \hspace{1cm} (1.1)

and are seen in Super–K via elastic scattering:

\[ \nu_e + e^- \rightarrow \nu_e + e^- \]  \hspace{1cm} (1.2)

Based on this data set, by far the world’s largest single sample of solar neutrino events, our most recent results, representing 1496 live days of analyzed data, spanning the period of May 31, 1996 to July 15, 2001, will be presented below.

Even as many of its members were busy working on the refurbishment and reconstruction of the detector, Super–K’s low-energy group has had a scientifically productive year, turning out three quite diverse articles in refereed journals.

Using data collected between April, 1996 and May, 2000, the first paper \(^\text{3}\) was a search for correlations between Super–K’s neutrino events and BATSE’s collection of gamma-ray bursts. The second paper \(^\text{4}\) was a global analysis using our 1496 days of data in combination with data from SNO, Homestake, Gallex/GNO, and SAGE to map out the remaining solar neutrino oscillation solutions. Finally, the third paper \(^\text{5}\), also using 1496 days of data, was a search for signals in Super–K resulting from relic supernova neutrinos.

The UCI group continues to play a central role in the Super–Kamiokande solar neutrino effort. From UCI hardware which keeps the air Radon free, to UCI computers and custom online software which allow the collection of super low-energy data, to UCI manpower conducting calibration of the detector, to UCI’s analyzing of the precisely calibrated data so acquired, to

\(^\text{5}\)M. Malek et al., submitted to Phys. Rev. Lett., hep-ex/0209028
1.4–2

UCI personnel writing and editing the resulting refereed journal articles, to our preparing for the future of Super–K, we are intimately involved with virtually every aspect of Super–K’s low-energy group: a true success story of international scientific cooperation.

1.4.2 Recent Results of the Solar Neutrino Analysis

Solar Neutrino Flux

Our standard method of displaying the solar neutrino signal is through the use of \( \cos \theta_{\text{sun}} \) plots, where \( \theta_{\text{sun}} \) is the angle between a reconstructed low-energy event’s direction and the direction defined by a line drawn between the Sun’s current position and the vertex position. This is depicted graphically in Figure 1.8.

The solar neutrino signal for the energy range 5.0 MeV to 20.0 MeV is shown in Figure 1.9. The peak above the background in the direction of \( \cos \theta_{\text{sun}} = 1 \) (i.e., originating from the direction of the Sun) are our solar neutrinos. There are some 22,400 events under the peak and above the background. This plot is one of the recent official results of the ongoing Super–K solar neutrino analysis, and represents the end result of all reduction and background suppression for 1496 live days of unified low-energy [LE] (6.5 MeV and above) and super low-energy [SLE] (below 6.5 MeV) data and 22.5 ktons of fiducial volume.

Note that, unlike atmospheric neutrinos, one can only identify solar neutrinos in a statistical fashion. No one has yet devised a way to prove that any given event in our detector actually originated from the Sun. For this reason, reducing the sea of background events under the solar peak is of central importance in all low-energy investigations.

The best fit to the data points is given by the flux predicted by the BP2000 version of the Standard Solar Model \(^6\) multiplied by a factor of 46.5%. More specifically, we measure:

\[
\text{flux} = 2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{syst.}) \times 10^6/\text{cm}^2/\text{sec} \tag{1.3}
\]

and

\[
\frac{\text{Data}}{\text{SSM}_{BP2000}} = 0.465 \pm 0.005(\text{stat.}) \pm 0.016(\text{syst.}) \tag{1.4}
\]

This measurement of flux well below the predicted value is one of the manifestations of the so-called “solar neutrino problem,” and as it happens a result near 50% is rather suggestive. If electron neutrinos are in fact oscillating to a single (unseen) species and back again, and if they have fully oscillated many times by the time they reach the Earth, then we would expect to measure exactly 50% of the predicted flux. Since it has become widely ac-
Figure 1.9: Solar neutrino signal between 5.0 MeV and 20.0 MeV. This is the result of 1496 live days of data and a 22.5 kton fiducial volume. The line is a fit to 46.5% of the BP2000 SSM.

It is now accepted that atmospheric muon neutrinos are in fact oscillating\(^7\), and in light of recent SNO results\(^8\), neutrino oscillations now look like a very probable answer to the solar neutrino problem. More on this in later sections.

**Day/Night Effect**

Figure 1.9 contains all the solar neutrino data – if the data are broken down into bins based on where the Sun was in relation to the horizon at the time the signal was received we get Figure 1.10. The bins on the right side of the plot are defined in the upper part of the figure.

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1.4. SOLAR NEUTRINOS AT SUPER–KAMIOKANDE

Figure 1.10: Day/night variation in solar neutrino signal between 5.0 MeV and 20.0 MeV. This is the result of 1496 live days of data and a 22.5 kton fiducial volume. The nighttime angular divisions are defined in the diagram in the upper part of the figure.

From Figure 1.10 it is readily apparent that there is little variation between our daytime and our nighttime solar neutrino signals. At present our official value for the overall day/night difference is as follows:

\[
\frac{D - N}{(D + N)/2} = -0.021 \pm 0.020(\text{stat.}) \pm 0.013(\text{syst.}) \quad (1.5)
\]

We have observed over 22,000 solar neutrinos between 5.0 MeV and 20.0 MeV since the start of the experiment, and are now recording just a 1σ difference in the day vs. night signals. Continued acquisition and analysis of Super–K’s data should allow us to resolve conclusively whether there is a hint of a day/night effect or not.
Seasonal Variation of Flux

Another interesting study which can be performed by breaking up the data is the search for seasonal variations in the flux. Such variations would be due to vacuum oscillations as the Earth moves around the Sun. Our results are shown in Figure 1.11. The wavy line represents the expected $\frac{1}{r^2}$ variation in the flux due to eccentricity of the Earth’s orbit. It can be seen that the data lie along the expected line with no strong deviations. In fact, the fit to the expected no-vacuum-oscillation line is quite good, much better than the fit to flat. As such, this represents the first ever demonstration of the eccentricity of the Earth’s orbit via inverse square variations in the solar neutrino flux. Not the easiest way to show Newton and Kepler were right, to be sure, but rather remarkable nonetheless. That being said, it will nevertheless be necessary to collect more data and shrink the error bars some more before we will be able to state conclusively whether or not there is any unexpected behavior going on as the Earth swings around the Sun. Ideally, we would like to acquire sufficient statistics to enable us to make such seasonal plots for a variety of different energy bins.

Energy Spectrum

Perhaps the most powerful test of oscillations is made by looking at the energy spectrum of the recoil electrons from the $^8$B solar neutrinos. Assuming that neutrinos are massive, neutrinos of a given energy will have an opportunity to execute a given number (or fractional number) of oscillations before reaching Super–Kamiokande. Therefore, deviations from the predicted spectral shape would constitute rather strong evidence of oscillations, since neutrinos of certain energies would then be more (or less) likely to be seen in our detector than neutrinos of other energies.

The results of our energy spectrum analysis can be seen in Figure 1.12, where the data points have been divided by the non-oscillating prediction for each bin. If these points fell in a straight, flat line then they would be consistent with an unoscillated spectrum. In fact, the present shape seen in Figure 1.12 has a remarkably good fit to flat. This lack of deviations will allow us to rule out certain oscillation hypotheses in coming sections.
1.4. SOLAR NEUTRINOS AT SUPER–KAMIOKANDE

1.4.3 Solar Neutrino Oscillation Analysis

Oscillation Signatures

In addition to a simple reduction of the overall solar neutrino flux, the presence of solar neutrino oscillations has the potential to cause three distinct effects in Super–Kamiokande’s low-energy data set:

1. a distortion of the energy spectrum
2. a zenith-angle dependent flux (day/night effect)
3. a seasonal dependence of the flux (seasonal variation)
Figure 1.12: Energy spectrum of solar neutrino recoil electrons, divided by theoretical predictions, between 5.0 MeV and 20.0 MeV. This plot contains 1496 days of data within our usual 22.5 kton fiducial volume. Deviations from a flat distribution would have constituted evidence of MSW neutrino oscillations. However, the fit to flat is a good one.

Super–Kamiokande has looked for distortions of the spectrum and time variations of the flux. The results of these studies, which in many ways represents the main conclusions of our solar neutrino analysis, will now be presented.

Analysis of the Zenith Angle Spectrum

Neutrino flavor conversion due to oscillations depends on the neutrino energy and the distance-of-flight. In addition to a conversion in vacuum, a matter-induced resonance in the sun (MSW effect) may sufficiently enhance the disappearance probability of solar neutrinos even for small neutrino mixing.
Matter effects inside the earth lead to flux variations depending on the solar zenith angle $\theta_z$. So far, two-neutrino oscillation models are able to accommodate all solar neutrino measurements. As in the atmospheric sector, two parameters describe the model: the mass squared difference between the neutrinos, $\Delta m^2$, and the mixing angle $\theta$. In the MSW region of $\Delta m^2$ (between $10^{-3}$ and $10^{-8}$ eV$^2$), three solutions exist, the large mixing angle solution (LMA; $\Delta m^2$ between $2 \cdot 10^{-4}$ and $10^{-5}$ eV$^2$), the small mixing angle solution (SMA; $\Delta m^2$ between $10^{-5}$ and $4 \cdot 10^{-6}$ eV$^2$) and the low solution (LOW; $\Delta m^2$ about $10^{-7}$ eV$^2$). Below the MSW region there is a vacuum oscillation region (VAC; below $10^{-10}$ eV$^2$) and a transition region, the quasi-vacuum oscillation region (quasi-VAC; between $10^{-10}$ eV$^2$ and $10^{-8}$ eV$^2$). In the MSW region, the largest sensitivity of Super-Kamiokande can be achieved combining spectral distortion and zenith angle variation. This analysis was done by the UCI group.

In the last year, the analysis was improved to include the uncertainty in the $^8$B neutrino spectrum, the SK energy scale deviation and the SK energy resolution deviation as separate systematic uncertainties, rather than describing all three as one systematic uncertainty. The oscillation constraints are not affected by this different treatment. The analysis was also extended to the “dark side” (mixing angle bigger than $\pi/4$) of the parameter space. The SK and SNO combined analysis was extended to a “global analysis” which includes the radio-chemical experimental results.

Oscillation Results

Since we last addressed this issue in print, the addition of 300 more live days of SK low energy data has further strengthened the oscillation constraints. Figure 1.13 shows the zenith angle spectrum using the full 1496 days of SK-I livetime and the best oscillation fits of the SMA and quasi-VAC solutions (shaded bands in the upper panels) as well as the LMA and LOW solutions (bands in the lower panels) to SK data and the rates of the other solar neutrino experiments — Homestake, Gallex/GNO, SAGE, and SNO. To obtain the dashed boundary of each band, the $^8$B and the $\nu_{hep}$ flux are varied to fit all solar data. The solid boundaries (and the lines in the panels on the right) are found by varying these fluxes as well as the peak of the $^8$B neutrino spectrum, the SK energy scale and resolution deviations, and the

---

$\tan^2 \theta = \frac{0.26}{3.8}$

$\Delta m^2 = 7.85 \times 10^{-11} \text{ eV}^2$

$\tan^2 \theta = \frac{0.69}{1.4}$

$\Delta m^2 = 6.68 \times 10^{-10} \text{ eV}^2$

$\tan^2 \theta = 0.0016$

$\Delta m^2 = 4.6 \times 10^{-6} \text{ eV}^2$

$\cos \theta_z$

Figure 1.13: Super-K Zenith Angle Spectrum.
SK total rate systematic uncertainty, yielding a better fit to the SK data. The panels on the left show the expected but unobserved spectral distortions which strongly disfavor the SMA solutions (light gray) and VAC solutions (dashed line). The right-hand side panels show zenith angle distributions in six energy ranges. The LOW solution (light gray) is disfavored. The quasi-VAC solution (dark gray) is disfavored by the data of the other solar neutrino experiments.

Figure 1.14 (a) shows the area of parameter space excluded by the shape of the zenith angle spectrum, the day/night spectrum and the spectrum. These excluded regions are independent of the SSM neutrino flux predictions. Using in addition the $^8$B neutrino flux constraint of the SSM, the allowed areas of Figure 1.14 (b) result. When the SK excluded area is overlaid with oscillation constraints from other experiments (see Figure 1.15), only large mixing angle solutions are consistent with both the SK zenith angle spectrum

Figure 1.14: Excluded (left panel) and allowed (right panel) using Super-Kamiokande's spectrum (hatched area), zenith angle spectrum (gray area) and day-night spectrum (inside dashed line) at 95% C.L.
Figure 1.15: Area excluded by the SK zenith angle spectrum shape (dark gray) overlaid with the area allowed by SNO data (gray area), Gallium data (hatched area) and Homestake data (inside gray lines).
1.4. SOLAR NEUTRINOS AT SUPER–KAMIOKANDE

![Diagram showing the allowed regions for neutrino oscillations.](image)

Figure 1.16: Area allowed by SK and SNO data (gray shaded areas on the left), SK and radio-chemical experiments (hatched areas on the left) and all solar neutrino data (shaded area on the right).

and the other experimental data.

UCI has extended the analysis of the zenith angle spectrum to perform a combined fit of SK and SNO data. Figure 1.16 (a) shows in light gray the allowed region based on the SK zenith angle spectrum, the SK elastic scattering rate (with electrons) and the SNO charged-current interaction rate (with deuterium). The dark gray allowed regions include additionally the SNO neutral-current interaction rate. The LMA solution is favored by this combined fit; the result is independent of any SSM neutrino flux prediction. The same figure also shows a hatched, allowed region based on a combined fit to SK, Homestake, Gallex/GNO and SAGE data (using the SSM neutrino flux predictions except for the hep flux). All solutions but LMA are disfavored at about 95% C.L.

Figure 1.16 (b) gives the result of a combined fit to all solar neutrino
1.4.14 TASK A

Data (using the SSM neutrino flux predictions except for the $^8$B and hep flux). Only LMA solutions appear at 95% C.L. Table 1.1 lists the parameters of the best fits to four solutions. The $\Delta \chi^2$ of the zenith angle spectrum shows the power of the SK spectral and solar zenith angle data: the SMA is excluded, the LOW is disfavored. The quasi-VAC solution is disfavored by an interplay of the rates of all experiments. Figure 1.17 displays the $\Delta \chi^2$ of various oscillation fits as a function of just one oscillation parameter. The details of the calculation are explained in our recently published Phys. Lett. B paper 10, which was written and edited at UCI. In fact, the great majority of this oscillation work has been done at UCI, and currently constitutes the cutting edge of the low-energy group’s physics results.

<table>
<thead>
<tr>
<th>Oscillation Solution</th>
<th>LMA</th>
<th>LOW</th>
<th>quasi-VAC</th>
<th>SMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^2$ [eV$^2$]</td>
<td>$6.6 \times 10^{-5}$</td>
<td>$7.2 \times 10^{-8}$</td>
<td>$6.68 \times 10^{-10}$</td>
<td>$4.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\tan^2 \theta$</td>
<td>0.42</td>
<td>0.63</td>
<td>1.4</td>
<td>0.0016</td>
</tr>
<tr>
<td>$\chi^2$ (46 dof; $p_{\chi^2}$)</td>
<td>42.8 (60.8%)</td>
<td>50.8 (29.2%)</td>
<td>51.6 (26.3%)</td>
<td>59.3 (9.0%)</td>
</tr>
<tr>
<td>$\Delta \chi^2$ (2 dof; $p_{\Delta \chi^2}$)</td>
<td>0.0 (100%)</td>
<td>8.0 (1.9%)</td>
<td>8.8 (1.2%)</td>
<td>16.5 (0.03%)</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{Zenith-Spectrum}} (p_{\Delta \chi^2})$</td>
<td>2.9 (1.2σ)</td>
<td>5.7 (1.9σ)</td>
<td>1.0 (0.5σ)</td>
<td>14.2 (3.3σ)</td>
</tr>
<tr>
<td>Gallium Rate [SNU]</td>
<td>69.9 (-0.2σ)</td>
<td>63.8 (-1.7σ)</td>
<td>63.6 (-1.7σ)</td>
<td>69.5 (-0.3σ)</td>
</tr>
<tr>
<td>Chlorine Rate [SNU]</td>
<td>2.99 (+1.9σ)</td>
<td>3.01 (+2.0σ)</td>
<td>3.08 (+2.3σ)</td>
<td>2.38 (-0.8σ)</td>
</tr>
<tr>
<td>Super-K Rate [%SSM]</td>
<td>46.3 (-0.1σ)</td>
<td>45.4 (-0.9σ)</td>
<td>45.0 (-1.1σ)</td>
<td>45.7 (-0.6σ)</td>
</tr>
<tr>
<td>SNO CC Rate [%SSM]</td>
<td>34.5 (-0.2σ)</td>
<td>37.6 (+1.2σ)</td>
<td>38.9 (+1.8σ)</td>
<td>40.5 (+2.5σ)</td>
</tr>
<tr>
<td>SNO NC Rate [%SSM]</td>
<td>103 (+0.2σ)</td>
<td>88 (-1.0σ)</td>
<td>76 (-2.0σ)</td>
<td>85 (-1.3σ)</td>
</tr>
</tbody>
</table>

Table 1.1: Best fit points of four oscillation solutions.

1.4.4 Future Solar Neutrino Data from Super–K

Although Super–Kamiokande has taken data for about five years, many of its solar neutrino precision measurements are still limited by statistical uncertainty and will therefore be improved by taking more data. In other cases, continued study of sources of systematic errors will prove decisive in yielding more physics results in the months and years to come.

During its run Super–Kamiokande has monitored the $^8$B flux for about half a solar cycle; observation over a full cycle will yield additional information about the stability (e.g., temperature and pressure) of the core of

Figure 1.17: $\Delta \chi^2$ as a function of $\tan^2 \theta$ (left) and $\Delta m^2$ (right) based on only SK data (upper panels), SK and SNO data (lower panels; gray lines), SK and radio-chemical data (lower panels; dotted lines) as well as all solar data (lower panels; black lines).

the sun. The daily variation of the high energy tail of $^8$B neutrinos (i.e., those above 11 MeV) gives the greatest sensitivity to LMA oscillations. Unfortunately, the statistical uncertainty for this tail is the largest of all the accessible energy regions. Consequently, continued, long-term observation of this high energy tail will further constrain LMA oscillations. Moreover, the yearly variation of the same high energy neutrinos will serve to place more stringent limits on vacuum oscillation parameters (currently marginally allowed by Super–K data alone at the 92% C.L.). At the same time, those vacuum oscillation parameters predict spectral distortions at about the same energy and can therefore also be constrained in this manner by prolonged exposure.

Upon completion of its repairs in late 2002, Super–K (or, more properly
speaking, SK–II) is expected to commence data-taking in the beginning of 2003. From UCI Monte Carlo studies, an energy threshold of about 6 to 7 MeV is expected, so SK–II will continue to take quality solar neutrino data. Spectral data with this somewhat higher threshold will be useful to further constrain the solar hep neutrino flux. SK will also resume its search for solar zenith angle variations of the solar neutrino flux, which are expected (albeit with a small amplitude) for the currently favored LMA solution. Even if KamLAND soon confirms the LMA solution, a positive indication for this variation would be of considerable interest since the correctness of the MSW description of neutrino propagation in matter has not yet been experimentally established. At UCI we are currently exploring ways to enhance Super–K’s sensitivity to the LMA solar zenith angle variation by exploiting the rapid oscillations of the regeneration effect as a function of zenith angle. Looking at this “fine structure” (and using higher energy data, where the amplitude of these oscillations is larger) we hope to reduce the minimum oscillation amplitude that SK can observe.

1.4.5 Summary and Conclusions

Even during a time of intense hardware work, the past year has seen a number of beautiful results come out of the Super–Kamiokande solar neutrino analysis. Measurements have been made which were simply impossible before Super–K came on-line six and a half years ago. The number of events we have collected long ago surpassed all similar, previous experiments (Kamiokande’s total solar neutrino sample, collected over ten years of running, had been equaled by Super–Kamiokande after only about two months of operations). These high-statistics, precision solar measurements have allowed us, in the last year alone, to produce three journal articles.

Echoing the now famous discovery of large atmospheric neutrino mixing in 1998, in 2002 large solar neutrino mixing was uniquely determined by using Super–K data alone. In combination with other experiments’ data, the LMA region has been conclusively selected at better than the 95% confidence level. Oscillations into purely sterile neutrinos are now looking so unlikely everywhere in phase space that the possibility can be all but disregarded.

Through its involvement at every stage of data collection, calibration, simulation, and analysis, UCI has led and is continuing to lead the way through the world of low-energy data. While most of our members have spent a large fraction of the last year and a half working in the Super–K tank,
this has nevertheless been another exciting and highly productive year for us. The near future promises yet more stimulating developments, as various in-house projects, including a reworked Super–K–II Intelligent Trigger, a revamped depth-dependent Monte Carlo, an improved understanding (and reduction) of our backgrounds, an enhanced oscillation analysis, an enriched extraction of relic supernova neutrino signals, and a search for a non-zero neutrino magnetic moment all continue to illuminate previously dark corners of the weakly-interacting world.
1.5 K2K Experiment

1.5.1 Status of the K2K experiment

The K2K experiment started in June 1999 and the first neutrino event was observed on June 19th, 1999. Since then we have taken data corresponding to 235 days of running until summer of 2001. This is about half of the aimed amount of data of the K2K experiment. Unfortunately the experiment planned to resume at the beginning of 2002 had to be postponed due to the accident at Super-Kamiokande (SK) detector in the fall of 2001, when many photo-multiplier tubes were broken. Currently the SK detector is being rebuilt and the K2K experiment is planned to restart at the end of December 2002. Here results of analysis based on 235 days data taken by 2001 is presented.

The neutrino beam was very stable during the data-taking. The direction of the beam has been controlled to better than 1 mrad as confirmed by muon profile monitor and muon range detector (MRD).

The neutrino oscillation analysis of last year was based only on the event rate [1]. Since then the full and improved error estimations as well as recalibration of near detectors have been performed. Both the event rate and the neutrino energy spectrum are taken into account this year to improve the estimate of the null oscillation probability and the allowed region of the neutrino oscillation parameters.

1.5.2 Neutrino oscillation analysis

Strategy of the analysis

If the neutrino oscillation occurs between muon neutrino ($\nu_\mu$) and tau neutrino ($\nu_\tau$) with the oscillation parameters found by the atmospheric neutrino measurements, the K2K experiment should see following two symptoms;

- The number of neutrino events observed at SK is smaller than that expected from the number of events observed at near detectors. Neutrinos generated at KEK are almost pure $\nu_\mu$s, while the $\nu_\tau$s resulting from their oscillations can interact only via NC processes due to the low beam energy.

- The shape of the neutrino spectrum is distorted because the probability of the $\nu_\mu \rightarrow \nu_\tau$ oscillation depends on the energy of the neutrino. For
the SK best fit parameters the maximum distortion is expected around 0.6 GeV.

The neutrino energy spectrum was measured by the 1KT water Cherenkov detector and fine-grained detectors: Sci-Fi and MRD.

Results of the oscillation analysis

Time coincidences between the neutrino interactions and the beam spills are used to select K2K neutrino events from a large SK data sample. The synchrotron proton beam creates the neutrino beam of 1.1 $\mu$s pulses per 2.2 s. For every SK event its trigger time $T(SK)$ is compared with the nearest beam spill start time $T(KEK)$ and a time difference $T_{diff} = T(SK)-T(KEK)$-TOF is calculated, where TOF is the flight time to cover the distance from KEK to SK. Figure 1.18 shows the distributions of $T_{diff}$ at various stages of contained event selection.

There are no other events around the beam events, which proves that the beam events can be clearly distinguished from other events such as atmospheric neutrino interactions. Thus a sample of 56 neutrino events in the SK fiducial volume (FV) has been selected from the data corresponding to 235 days by the summer of 2001.

The expected neutrino rate is based on the flux measurements at near detectors. In the absence of oscillations $80.1^{+5.4}_{-6.2}$ neutrino events are predicted.
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1.5–3

Figure 1.19: Reconstructed neutrino energy spectrum at SK

at the FV of SK. The error comes mostly from the systematic uncertainty of the extrapolation of the neutrino flux to the SK location.

The neutrino energies can be most reliably reconstructed for 29 single-ring $\mu$–like events and are displayed in Figure 1.19.

In order to obtain the expected neutrino spectrum the samples of quasi-elastic events have been selected from the 1 KT and fine-grained detectors. This spectrum is then multiplied bin by bin by the far-to-near ratios obtained from the beam MC simulations. In Figure 1.19 the spectra are shown in the absence of oscillations as well as for a set of best fit parameters: $\Delta m^2 = 2.8 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta = 1.0$.

The oscillation analysis is performed by maximum-likelihood method using both the number of observed events and the shape of the energy distribution. The probability that the measurements at SK can be explained by statistical fluctuations without neutrino oscillations is less than 1%.

The allowed region is shown in Figure 1.20. It is seen that at 90% c.l. the values of $\Delta m^2$ are between $1.5 \times 10^{-3}$ eV$^2$ and $3.9 \times 10^{-3}$ eV$^2$ for $\sin^2 2\theta = 1.0$.

Future plans

The tuning of the beam and a check of near detectors will start in December 2002 and the data taking will be resumed in January 2003. An increase of data statistics by a factor of two is expected by March 2005. We also keep
working on the reduction of systematic errors. (One example is described in the following section.)

1.5.3 Neutrino physics in near detectors

Large samples of neutrino interactions collected in the near detectors facilitate detailed studies of neutrino and nuclear physics. The basic studies in this field were very popular more than 30 years ago with the advent of the first neutrino beams, nonetheless, they were conducted with smaller statistics and never on water as the target. The latter is of great importance for Super Kamiokande studies of atmospheric neutrinos. The nuclear corrections for interaction in Oxygen nucleus were always under some doubt. Thus, proper tuning of the neutrino interaction model, applied by both K2K and Super Kamiokande, to the observations made in the near detectors is an additional very important outcome of the K2K experiment. In this regard, it is significant that the neutrino spectra of the KEK beam and that of atmospheric neutrinos are similar. They extend over the 1 GeV region where simple quasi-elastic and resonance production processes dominate. Studies of neutrino physics are a long term project. So far, however, some important results are available.

The first international workshop on neutrino-nucleus interactions in the few GeV region (Nuint-01 [2]) was successfully held on December, 2001 at
KEK. UCI group played important roles on neutrino MC simulator and the proton decay background study in this workshop. The second workshop (Nuint-02) has now been scheduled for December 2002 in UCI.

Here some interesting neutrino physics mainly studied by UCI are summarized. Some new results and studies added after the Nuint-01 are also mentioned.

Neutral current $\pi^0$ production.

The study of neutral current $\pi^0$ production at 1KT (including systematic error estimates) and its application to the atmospheric neutrino oscillation is finally completed. See [2] \textsuperscript{1} for more details. One UCI on-site researcher has been contributing to this study, especially on the 1KT data analysis, as a $\pi^0$ analysis group member. Now a paper is being prepared by a committee including two UCI physicists.

The main conclusions are:

- The double ratio $\frac{\left(\pi^0/\mu\right)_{\text{DATA}}}{\left(\pi^0/\mu\right)_{\text{MC}}}$ measured at 1KT is 1.02$\pm$0.02 (stat.$\pm$0.09 (syst.), i.e. MC reproduces data reasonably well.

- SK single $\pi^0$ result favors $\nu_\mu \rightarrow \nu_\tau$ oscillation. ($\nu_\mu \rightarrow \nu_\tau$ is disfavored at the 1.5$\sigma$ level.)

The neutral current $\pi^0$ measurement is also very important for the $\nu_e$ appearance experiment, because the $\pi^0$ background via $\nu_\mu$ interaction is much higher than the $\nu_e$ signal via the charged current quasi elastic scattering in the standard sample of $\nu_e$ candidates (fully contained 1 ring electron-like events). The neutral current $\pi^0$ is reconstructed as one electron-like ring when the two gamma rings are overlapped or the lower energy ring is not reconstructed. The special $\pi^0$ fitter developed at UCI is expected to reduce the $\pi^0$ background. Therefore the check of the performance of the $\pi^0$ fitter with the real data at 1KT is an important study. UCI group is going to study this.

\textsuperscript{1}Proceedings/Slides” →”New NC data from K2K 1kt water Cherenkov Detector”
Proton decay background study

The introduction of the proton decay background study using 1KT detector data is summarized in [2] \(^{12}\).

At the last report, we showed that agreements of basic distributions for \(\nu n \rightarrow \mu \pi^0 X\) (\(X\) is any invisible particles) called “\(\mu \pi^0\)” events such as total momentum distribution or total invariant mass distribution between DATA and MC are very good (These are also shown in [2].). This demonstrates that our ability to model the proton decay background interaction is well supported by the data. The main points of progress of last year are:

- An estimate of systematic errors at 1KT \((Preliminary)\)
- Prediction of the proton decay background of \(p \rightarrow e \pi^0\) mode in current SK data analysis
- Beginning of kaon production studies

Most dominant systematic errors on the number of the “\(\mu \pi^0\)” events come from the uncertainty of the reconstruction for multi-ring events at 1KT. The systematic error of the ring-counting is roughly estimated to be about 30% by comparing the standard automatic ring edge finding program to the manual one\(^{13}\). The systematic error of the particle identification (PID) is estimated to be about 20% by comparing the events with or without the PID cuts. The other systematic errors coming from uncertainties of the neutrino energy spectrum, neutrino interaction model etc. are estimated to be much less than those of the ring-counting and PID. Although these systematic error estimates are still preliminary, they are comparable with the statistical error (about 40%) of the “\(\mu \pi^0\)” events in the proton decay signal box at 1KT at this moment.

The dominant atmospheric neutrino backgrounds to the \(p \rightarrow e \pi^0\) search at SK come from \(\nu_e\) interactions. Figure 1.21 shows neutrino flux \(\times\) cross section for the atmospheric \(\nu_e\) at SK and the K2K \(\nu_\mu\) at 1KT, which is used to construct a weight function allowing to use the 1KT data for simulations in SK.

\(^{12}\)“Proceedings/Slides”→“Study of neutrino backgrounds to nucleon decay searches using K2K 1kton detector data”

\(^{13}\)The number of events applied by the manual fit was very small at this moment. We are going to increase the statistics soon.
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By combining with the relation between true neutrino energy and observed visible energy at 1KT, the number of background events in the current SK analysis is predicted as $0.12 \pm 0.05 \text{ (stat.)} \pm 0.05 \text{ (syst.) events/1489 days (Preliminary)}$, i.e. negligibly small in the current SK data sample. On the other hand, the background estimated by the atmospheric neutrino MC is $0.17 \pm 0.10 \text{ (stat.) events/1489 days}$. They are consistent with each other.

The proton decay mode $p \rightarrow \bar{\nu}K^+$ is another dominant mode predicted by SUSY-GUTs. The atmospheric neutrino interaction $\nu p \rightarrow \nu \Lambda K^+$ will become the limiting background on this mode with an expected rate of about 1 event/Mt·yr. In order to check the validity of the kaon production model, the charged current single kaon production $\nu n \rightarrow \mu \Lambda K^+ (K^+ \rightarrow \mu \nu)$ may be detectable at 1KT by requiring two muons with tens of ns time difference and the 2nd muon momentum $\sim 236 \text{ MeV}/c$. (the kaon decays at rest.) Figure 1.22 shows a typical time distribution for such two muon events.

According to the 1KT MC, a few dozens of such clear events are expected for 50 t fiducial and $10^{20}$ pot. Development of new tools to find such two muons and optimization of cuts are under study.

Currently one UCI researcher is preparing a paper with a summary of the proton decay background study.
Figure 1.22: Typical time distribution for $\nu n \rightarrow \mu \Lambda K^+ (K^+ \rightarrow \mu \nu)$ event at 1KT.

**Non-quasi elastic scattering measurement for spectrum analysis**

The neutrino energy is reconstructed from the muon momentum and its angle assuming a charged current quasi elastic (QE) interaction. However about half of the QE candidates (fully contained 1 ring muon-like events) at 1KT comes from the non-quasi elastic (nQE) events. The nQE contribution has to be then estimated using neutrino interaction models. Currently the (nQE)/QE ratio is treated as a representative parameter of the uncertainty of the neutrino interaction and is measured by the spectrum fit simultaneously. The fitting error is taken into account as systematic error on the measured neutrino energy spectrum.

In order to check the validity of our modeling of the neutrino interaction, the nQE events with a visible pion are analyzed. The single pion production events like $\nu p \rightarrow \mu p \pi^+$ or $\nu n \rightarrow \mu p \pi^0$ can be identified as 2 ring muon-like events or 3 ring one muon-like and two electron-like (whose invariant mass is in the $\pi^0$ mass region) events respectively because the proton in the final state is usually below the Cherenkov threshold and the charged pion is generally identified as muon-like event.

The measurement of the relative cross sections such as (fully contained 2 ring muon-like events)/(fully contained 1 ring muon-like events) could constrain the nQE/QE ratio. Moreover these nQE data analysis allows to study some neutrino interaction model parameters such as axial vector mass.
A comparison between DATA and MC for various distributions and various models is now under study including estimates of systematic errors on the relative cross section measurements.

1.5.4 UCI contributions to calibrations and detector maintenance.

Since the beginning of the experiment the UCI group has been responsible for calibration and tuning of the 1KT detector simulation using cosmic ray muon data. Most of physics results obtained from the 1KT detector strongly rely on these efforts.

Here some recent updates are described.

**Absolute energy scale calibration**

This year not only vertical but also horizontal cosmic ray through going muons data have been analyzed. When combined with an improved Xe data analysis the uncertainty of the absolute energy scale has been decreased to less than $\pm 5\%$. This result directly improves the measurement of the neutrino energy spectrum at 1KT detector.

Figure 1.23 shows the agreement of the absolute energy scale between DATA and MC for cosmic ray stopping muons and neutrino induced neutral current $\pi^0$'s events.
Relative PMT gain calibration

To confirm the relative PMT gain calibration carried by Xe data, UCI group has been studying the decay electrons from cosmic ray stopping muons. UCI installed the trigger scintillation counters and made a part of the trigger logics.

So far over 60,000 stopping muons have been recorded. The data quality has been studied using distributions of decay time, PID etc. and has been found to be very good. For example, Figure 1.24 shows the decay time distribution for one typical run. The exponential fit result is consistent with the expected mean lifetime. (Note: due to nuclear capture for negative muons, the measured lifetime is slightly shorter than that for only positive muons.)

Currently we study the decay electron mean momentum and its dependence on various exit positions, the parent muon polarization effect etc.
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Tuning of the 1 KT detector simulation

Cherenkov light transportation through water is critical for the 1KT detector simulation. Rayleigh and Mie scattering, absorption as well as reflection from PMTs and the inner wall have to be carefully taken into account. Parameters used to describe those processes can be tuned using CR muons and laser light. The current 1KT detector simulation program uses the parameters tuned by UCI group to through going and stopping muons data. Those parameters are currently updated by a graduate student employed by UCI. Also laser measurements at various wavelengths have been done within last year and are now analyzed and compared with the muon parameters.

Figure 1.25 shows the results of the measurement of the Rayleigh scattering coefficient using the laser data. The data points nicely follow the theoretically expected dependence of $1/\lambda^4$.

Management of offline analysis of 1kt detector data

UCI is taking responsibility of the management of the 1KT offline data analysis libraries and the reconstruction processes.
Operation of water purification system of 1kt detector

UCI group is responsible for the operation of the water purification system of the 1KT detector. The water quality measured by temperature, resistance, etc. has been kept stable except for a few days during KEK regular summer blackout.

Maintenance of the water system is the responsibility of our in-resident researcher; it also requires 4 yearly visits from California-based personnel and Japanese chiller company.

The water quality is now also monitored by the real-time off-line web monitor. A new computer has been installed at UCI for this purpose. In the future some video cameras are going to be installed in the water system tent house to monitor the hardware status visually.

1.5.5 Recent K2K publications (2001-2002)

Some papers [3, 4] concerning the performance of the near detector have been published recently or will be published soon. They are co-authored by some UCI group members, who contributed to detector construction and the data analysis at the early stage of its development.

References


The proceedings of the workshop will be published in Nuclear Physics B - Proceedings Supplement in fall, 2002.

1.6 The Future – JHF

1.6.1 Motivation and Status

Super-Kamiokande’s atmospheric neutrino results and solar neutrino data (in combination with the Sudbury experiment) have established the reality of neutrino oscillation conclusively. Study of neutrino mass splittings and mixing angles, an entirely new sector of physics outside the Standard Model as understood until a few years ago, has already revealed surprises. The atmospheric mixing angle ($\theta_{23}$) is apparently almost maximal, very near $\pi/4$; indeed, the weak neutrino eigenstates $\nu_\mu$ and $\nu_\tau$ have no well-defined masses at all but are almost equal mixtures of two mass eigenstates. Solar neutrino data increasingly favors a large mixing angles ($\theta_{12}$). Yet the CHOOZ experiment has demonstrated that the third mixing angle ($\theta_{13}$) is relatively small, $\sin^2 2\theta_{13} < 10\%$. Clearly the leptonic mixings bear little resemblance those of the quarks – a new and fundamental revelation. The three neutrinos are either nearly degenerate at some unknown common mass value below about 1 eV, or exhibit a hierarchy which strongly suggests a new, large “see-saw” mass scale close to the extrapolated point of coupling unification. In this case, neutrinos are Majorana particles and neutrinoless double $\beta$-decay should occur. If the LSND neutrino oscillation result is confirmed, it implies a fourth neutrino species, or the equally unexpected non-equivalence of neutrino and anti-neutrino masses; in either case, precision investigation of neutrino oscillation becomes even more essential.

At a minimum, two mixing parameters remain to be pinned down: the small mixing angle $\theta_{13}$ and the leptonic analog of the hadronic $CP$-violating phase, $\delta_{CP}$. Establishing some lower bound on $\theta_{13}$ is the first priority, since if this angle is less than a degree ($\sin^2 2\theta_{13} < 10^{-3}$), measurement of $\delta_{CP}$ will require a neutrino factory, if it is observable at all. Likewise, finite $\theta_{13}$ is required to determine the order of the mass hierarchy ($\text{sgn} \Delta m_{13}^2$) via matter effects at accelerator energies.

These physics imperatives have motivated study of long-baseline experiments using extremely intense “superbeams” produced by high-power proton sources. Large proton luminosities and neutrino fluxes are required to extend sensitivity to the small mixing angle $\theta_{13}$ significantly beyond CHOOZ. Disappearance experiments cannot achieve the level of precision required, hence the $\nu_e$ content of the beams must be carefully controlled and a large far detector with good $\nu_e/\nu_\mu$ discrimination is required to detect a small appearance
The furthest advanced and most detailed of these superbeam studies is the JHF-Kamioka long-baseline proposal.[1] As described below, in Phase I of this experiment the 0.75 MW\textsuperscript{14} 50 GeV proton synchrotron at JHF (JAERI) would direct a narrow-band, \( \sim 700 \) MeV off-axis beam of \( \nu_\mu \), designed to contain only 0.2\% \( \nu_\epsilon \) contamination, 295 km to Super–Kamiokande. Using the measured performance of the (full) Super–Kamiokande detector and the well-established resolutions of existing reconstruction tools, a factor \( \sim 20 \) improvement on the CHOOZ \( \sin^2 2\theta_{13} \) sensitivity is expected in a 5-year run. An order of magnitude improvement in the precision of \( \sin^2 2\theta_{23} \) and \( \Delta m^2_{23} \) and a sensitive direct search for \( \nu_\mu \rightarrow \nu_{\text{sterile}} \) oscillation using neutral current interactions are also planned.\textsuperscript{15}

The 50 GeV proton synchrotron is under construction; the neutrino beamline’s prospects for approval, with completion in early 2007, are considered good. As the most mature and compelling prospect for pursuing long-baseline oscillation physics beyond K2K, MINOS and the CERN-Gran Sasso experiments, the JHF-Kamioka project has generated strong interest from neutrino physicists in North America and Europe and an international collaboration will be formed to elaborate the technical design of the experiment some time in the coming year. One of the most attractive features of the JHF-Kamioka project is that it leverages the existing resources and scientific capital of Super–Kamiokande to launch a new, major experiment affordably and on a very competitive timetable. Recommissioning Super–Kamiokande is therefore not just a short-term investment to complete the experiment’s present physics program; it is also an essential down-payment on a powerful and unique future program ripe with discovery potential, which could produce dramatic results at a modest incremental cost in a little over five years.

\subsection*{1.6.2 Off-Axis Neutrino Beam}

The design of the neutrino beam is guided by the primary discovery channel of the experiment, namely detection of \( \nu_\mu \rightarrow \nu_\epsilon \) oscillation via \( \nu_\epsilon \) appearance at the level of a few per mille. To obtain a measurable signal, thousands of

\textsuperscript{14}For comparison, the power of the 12 GeV KEK proton synchrotron used in K2K is only 0.005 MW; NUMI is 0.4 MW.

\textsuperscript{15}A possible second phase of the experiment, using upgraded (4 MW) proton intensity and a hypothetical Mton-scale water detector would be sensitive to \( \delta_{CP} \) over most of the parameter-space accessible to a neutrino factory.
unoscillated $\nu_\mu$ interactions must be collected. The linear rise of the neutrino cross-section with energy thus favors a high-energy beam. Background considerations, on the other hand, require the opposite – a low-energy beam – since both $\nu_e$ contamination from kaon decay in the beam and neutral-current background from misidentification in the far detector also increase sharply with energy. A typical wide-band neutrino beam, even one peaked around 1 GeV, includes a high-energy tail which contributes disproportionately to these backgrounds. The novel solution to these competing considerations is to place the far (and near) detector a few degrees off the axis of the beam. The kinematics of pion decay then produce a strong enhancement around a particular angle-dependent energy (chosen to maximize the oscillation probability given $\Delta m^2$ and $L$), while strongly suppressing the $\nu_e$ component and high-energy tail of the beam. As Figure 1.26 shows, the (useful) neutrino flux at the peak of such an off-axis beam (with maximum oscillation probability) is actually higher than at the peak of the wide-band, on-axis beam, further improving the signal to noise.

For the best possible characterization of the unoscillated neutrino beam (including $\nu_e$ contamination) and to measure the rate of neutral current background, two near detector facilities – one at the production source, as in K2K, and another 1-2 km downstream\textsuperscript{16} are planned.

### 1.6.3 Super–Kamiokande as Far Detector

Super–Kamiokande, fully restored to its original sensitivity, is ideally suited to the requirements of a $\nu_e$ appearance experiment. The detector’s large mass facilitates an experiment below 1 GeV, where the signal:noise is optimal but the cross-section is low. Most visible neutrino reactions at these energies are quasi-elastic, and therefore easily identified as either $\nu_\mu$- or $\nu_e$-induced using the Cherenkov pattern and muon decays. For an appearance experiment, the particle identification criteria can be tightened to reduce lepton misidentification to a negligible level with only slight loss of efficiency for the signal. Another advantage of the narrow, off-axis beam tuned to the oscillation maximum is that approximately half the $\nu_\mu$ oscillate to $\nu_\tau$ which are then below charged-current threshold.

The remaining detector-related background arises from neutral current $\pi^0$ production.

\textsuperscript{16}The neutrino spectra at this distance are identical to those at the far detector; the flux can therefore be extrapolated trivially as $1/r^2$. 
Figure 1.26: Comparison of the JHF wide-band (purple) and 2° off-axis (green) beams. The off-axis beam is narrowly peaked at an energy chosen to maximize the oscillation probability at 295 km for $\Delta m_{23}^2 = 3 \times 10^{-3}$ eV$^2$, and the background-rich high-energy tail of the wide-band beam is suppressed. The higher-energy, NUMI (0.4 MW, Ph2LE) beam 10 km off-axis at 730 km is also shown (red).[1, 2]
Production of secondary hadrons is largely suppressed by the relatively low-energy of the beam. Moreover, most $\pi^0$ produced are themselves low-energy and produce two distinct rings, excluding them as $\nu_e$ candidates. For the others, we have developed a specialized $\pi^0$ identification algorithm which searches single, showering events for the best direction and energy of a second ring candidate. For most $\nu_e$ quasi-elastic events with only a single primary electron, this second ring candidate is either coincident with the first ring, or very low energy; in either case the primary and secondary rings sum to an invariant mass close to zero. For $\pi^0$, however, the second ring candidate often corresponds to the missing $\gamma$, and the two rings reconstruct to a relatively large invariant mass, consistent with that of a $\pi^0$. After all selections, the total instrumental background from neutral currents and $\nu_\mu$ charged-currents is reduced to the level of $\nu_e$ contamination in the beam; further improvements in the detector performance, while possible, would yield diminishing returns. The need for exceptional $\mu/e$ and $\pi^0/e$ discrimination in the $\nu_e$ appearance search are a strong motivation for the eventual restoration of full inner-detector photocathode coverage, because the performance of pattern recognition algorithms (particle ID and ring-finding) depends strongly on the granularity with which the Cherenkov light pattern is sampled. This is clearly illustrated in Figure 1.27.

As Figure 1.28 shows, the moderate beam energy and resulting predominance of quasi-elastic reactions also allows precision measurement of $\theta_{23}$ and $\Delta m^{2}_{23}$. Using only the detected lepton’s momentum and angle, the incident neutrino energy can be inferred with sufficient precision to make the oscillatory pattern of $\nu_\mu$ disappearance manifest when plotted vs. $L/E_{\nu}^{recon}$. The position of the oscillation maximum permits precision measurement of $\Delta m^{2}_{23}$; comparison of the rate at $\langle E_{\text{beam}} \rangle$ compared to $E \gg \langle E_{\text{beam}} \rangle$ (using the un-oscillated spectrum measured at the 1-2 km near detector as a reference) likewise provides a sensitive estimate of $\sin^2 2\theta_{23}$.

**1.6.4 Phase I Sensitivity**

It should be emphasized that efficiencies and backgrounds for the JHF-Kamioka project have been estimated using a neutrino interaction model validated by K2K near-detector data, a detector simulation tuned to agree precisely with the real experiment’s performance over the first 5 years of operation, and reconstruction tools which are already in use. Hence, these projections of detector performance are in no sense optimistic “best guesses”
Figure 1.27: A real event from the K2K beam (which contains only 1% $\nu_e$ impurity) in Super–Kamiokande, demonstrating rejection of $\pi^0$ contamination in the future JHF-Kamioka project. Although only a single showering ring (the black circle at center) was evident in this event (making it appear to be $\nu_e$-induced), a specialized likelihood fitter developed by American collaborators successfully identified another ring candidate (blue circle right of center) which, together with the primary ring, reconstructs to the $\pi^0$ mass and tags the event as a neutral current interaction. This event illustrates the importance of restoring the full inner detector photocathode coverage to any future $\nu_e$ appearance search, as well as proton decays involving $\pi^0$.

typically found in preliminary studies but rather, conservative; with five years remaining to optimize JHF-specific analyses before the beam is available, improvements are certainly possible. This section describes the expected physics sensitivity of the Phase I experiment, as estimated by the Japanese JHF–Kamioka working group.[1]

Figure 1.29a shows the expected $\nu_e$ appearance signal and background in
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Figure 1.28: Neutrino energy reconstruction for the off-axis beam. Left: Reconstructed vs. true neutrino energy, showing a band of well-reconstructed quasi-elastic events along the diagonal, and feed-down of inelastic events. Right: Neutrino energy resolution, showing the contribution of quasi-elastic interactions (red) and the inelastic tail (unshaded). Charged-current quasi-elastic interactions allow the neutrino energy to be accurately determined using the measured lepton momentum and angle from the known beam direction. Inelastic events can be subtracted when fitting the survival probability as a function $L/E_{\nu_{\text{recon}}}^{-1}$ to extract $\Delta m_{23}^2$.\[1\]

a five-year run ($10^{21}$ protons on target), assuming $\sin^2 2\theta_{13}$ is near the upper-limit set by CHOOZ. Figure 1.29b shows the projected 90% confidence level and $3\sigma$ sensitivities to the effective mixing angle $\sin^2 2\theta_{1\mu} (\equiv 0.5 \sin^2 2\theta_{13})$ as a function of the exposure; for a five-year run the improvement is approximately a factor 20 over the present CHOOZ limit.

Turning to the $\nu_{\mu}$ disappearance experiment, Figure 1.30 shows the clear oscillatory dependence of the $\nu_{\mu}$ suppression on reconstructed neutrino energy after subtracting the background from inelastic events. Including reasonable systematic uncertainties, the survival probability can be fit to extract precisely ($\sim 1\%$) measured values of $\sin^2 2\theta_{23}$ and $\Delta m_{23}^2$, as demonstrated in Figure 1.31 for two values of $\sin^2 2\theta_{23}$.

Finally, the rate of neutral current interactions (tagged by single $\pi^0$) can be used to directly discriminate between the $\nu_{\mu} \to \nu_\tau$ and $\nu_{\mu} \to \nu_{\text{sterile}}$ oscillation hypotheses. Figure 1.32 shows the rate of identified single $\pi^0$ for both hypotheses, as a function of $\Delta m_{23}^2$. Since $\nu_{\mu} \to \nu_\tau$ oscillation does not reduce the rate of neutral current interactions, while full $\nu_{\mu} \to \nu_{\text{sterile}}$
Figure 1.29: Left: Expected $\nu_e$ appearance signal (blue) and backgrounds (bottom histograms) in a five-year run, assuming the mixing angle $\sin^2 2\theta_{\mu e}$ (defined as $0.5 \sin^2 2\theta_{13}$) is near the upper limit set by CHOOZ). Right: 90% confidence level (bottom curves) and $3\sigma$ (top) sensitivity to $\sin^2 2\theta_{\mu e}$ vs. exposure. A five-year run will improve the present CHOOZ limit by a factor of 20.[1]

Figure 1.30: Probability of $\nu_\mu$ survival as a function of reconstructed neutrino energy, after subtraction of inelastic background in a five-year run. The oscillatory pattern of the flux suppression is dramatically apparent.[1]

mixing predicts more than a factor 2 suppression of the single $\pi^0$ rate, the measurement is sensitive to even small admixtures of $\nu_{\text{sterile}}$.

References

Figure 1.31: Measurement precision for $\sin^2 2\theta_{23}$ (left) and $\Delta m^2_{23}$ (right) vs. $\Delta m^2_{23}$, for $\sin^2 2\theta_{23} = 1$ (black curve) and 0.9 (red), for a five-year run. Both parameters can be determined with a precision of about 1%. Note that statistical and systematic errors are included in these estimates.[1]

Figure 1.32: Comparison of single-$\pi^0$ event rates for $\nu_\mu \rightarrow \nu_\tau$ (green, showing a band with the uncertainty on the prediction) and $\nu_\mu \rightarrow \nu_{\text{sterile}}$ (blue) in a five-year run. The neutral current event rates allow the two hypotheses to be distinguished for all $\Delta m^2_{23} > 10^{-3}$ eV$^2$.[1]