THE SUPER-KAMIOKANDE PROJECT: NUCLEON DECAY AND ATMOSPHERIC NEUTRINOS

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ABSTRACT

This manuscript presents an overview of the current experimental situation regarding nucleon decay and the measured flux of atmospheric neutrinos. Previous and on-going experiments are reviewed, the data are presented, and new outstanding questions are posed. The Super-Kamiokande project is described and its expected sensitivity for improving measurements of the nucleon lifetime and the atmospheric neutrino spectrum are discussed.

1. Introduction

For the past few decades, several experiments in the field of particle astrophysics have been performed using large detectors and deep underground facilities. Many of these experiments have already produced significant results and, at the same time, have posed new questions to be investigated. The Super-Kamiokande project represents the next generation of large deep underground detectors. The significantly increased fiducial mass and the improved resolution of the detector will allow for measurements with increased sensitivity for nucleon decay, solar neutrinos, atmospheric neutrinos, and supernovae neutrinos. In this manuscript, an overview of the project is presented in Sec. 2. Sections 3 and 4 review the current experimental situation and expectations of Super-Kamiokande for a nucleon decay search and a measurement of the atmospheric neutrino flux, respectively.

2. Description of the Super-Kamiokande Project

Super-Kamiokande is a 50,000-ton ring-imaging water Cherenkov detector currently under construction at a depth of 2700 meters water equivalent (mwe) in the Kamioka Mozumi mine in Japan. A schematic representation of the detector is shown in Fig. 1. It consists of a stainless steel tank in the shape of a right circular cylinder, 39 m diameter and 41 m height, filled with purified water. The detector is optically segmented into an inner volume (34 m diameter, 36 m height) and an outer (anticoincidence) region of 2.5 m thickness on the top, bottom, and sides of the inner volume. The inner detector is viewed by 11,200 photomultiplier tubes (PMT's) of 50□cm diameter, uniformly distributed on the inner boundary giving 40% photocathode coverage. This extraordinary photocathode coverage and time resolution (2.5 ns at 1 p.e.) allows the detector to attain an energy threshold of 5 MeV and a vertex resolution of 10 cm for processes such as $p \rightarrow e^{+}\pi^{0}$. For through-going muons, the PMT configuration yields an angular resolution of ~1°. The total mass of water inside the inner detector PMT surface is 32,000 tons. The fiducial mass for the proton decay search, defined to be 2 m inside the PMT plane, is 22,000 tons allowing for partial lifetime sensitivities of > 10^{34} years for several modes.

The outer annulus of the detector is an anticoincidence region used to tag entering muons and low-energy components as well as to attenuate low-energy gammas and neutrons which cause background in the sensitive volume. It also compliments calorimetry in the inner detector by measuring the energy loss due to exiting particles. This outer detector region is viewed by 1860 PMT's of 20 cm diameter with wavelength shifter plates in the style of IMB-3. The walls of the anticoincidence region are made reflective to enhance light collection. The PMT's are mounted facing outwards on the same superstructure as the 50 cm PMT's of the inner volume. Also, an optical barrier is mounted on the same structure to separate the inner and outer regions.

2.1 Comparison with Other Experiments

The largest water Cherenkov detector (3300-ton fiducial mass) previously built was the Irvine-Michigan-Brookhaven (IMB) detector located in the Morton Salt Company Fairport Mine in Ohio. IMB operated successfully from September 1982 until April 1991, placing significant constraints on the nucleon lifetime into 35 possible decay modes. In addition, important results were published on atmospheric neutrinos, neutrino oscillations, neutron-antineutron oscillations, and monopole catalysis of nucleon decay. A highlight of IMB was the first detection of neutrinos from a supernova, SN1987A.

A second large water Cherenkov detector (1040-ton fiducial mass) is the Kamiokande experiment in Japan which commenced operation in July 1983 and continues even now. In addition to the same physics addressed by IMB, the large photocathode coverage of Kamiokande allowed for triggering on low-energy events (7.5 MeV) which resulted in the first direct, real-time observation of neutrinos from the sun. The observation of neutrinos from SN1987A, simultaneous with IMB, provided the first test of standard supernova theory with regards to neutrino production during collapse.

In Table 1, the physical parameters of Super-Kamiokande are listed in comparison with those of Kamiokande-III and IMB-3. With seven times larger fiducial mass and ten times the photocathode coverage of IMB, Super-Kamiokande will explore nucleon lifetimes to $>10^{34}$ years with a few years of running. The increased discrimination of showering and nonshowering events will greatly improve studies of particular nucleon decay modes and the atmospheric neutrino spectrum.

In Table 2, the detector performance parameters of Kamiokande-III, IMB-3, and Super-Kamiokande are compared. Energy and position resolutions are significantly improved, an essential feature for the elimination of background and the detection of low-energy interactions. These features will allow Super-Kamiokande to have sensitivity for detection of solar, atmospheric, and supernova neutrinos above a threshold of 5 MeV.

Figure 1. Schematic representation of the Super-Kamiokande detector.

Table 1: Comparison of the physical parameters of large water Cherenkov detectors.

Table 2: Comparison of the performance parameters of large water Cherenkov detectors.

3. Nucleon Decay

Nucleon instability, expected at some level in many extensions of the Standard Model, still offers a unique probe in searches for the ultimate theory of interactions. In this respect, the observation of nucleon decay would have more significant and far-reaching consequences than those from experiments seeking to fill existing gaps in the Standard Model, for example, by finding the top quark or the Higgs. The lifetime of the proton depends on the scale of grand unification as determined by the convergence of the three fundamental running coupling constants at a single point at very high energy. Recent measurements of these coupling constants at LEP[1,2] have resulted in much better predictions of the proton lifetime than was previously possible. These lifetimes are within the reach of a detector the size and resolution of Super-Kamiokande.

Super-Kamiokande will be the largest nucleon decay detector ever constructed. In terms of its sensitive mass (22,000 metric tons), it is larger than the sum of the fiducial masses of all the other detectors ever built (NUSEX, Soudan I, IMB, Kamioka, Soudan II, Frèjus, and KGF; see Table 3). Super-Kamiokande will not only have seven times the fiducial volume of IMB, it will also have ten times the light collection capability. This will result in a substantially higher efficiency for low-light level decay modes. When coupled with lower background rates from atmospheric neutrinos (due to better energy and track resolution), this will lead to at least an order-of-magnitude increase in nucleon decay detection sensitivity for most decay modes. It is this ten-fold improvement that will allow Super-Kamiokande to test theories (such as Flipped SU(5) x U(1)) that predict proton decay in the range $10^{33\text{-}35}$ years.

Table 3. Comparison of nucleon decay detector masses.

Detector	Mass (kiloton)	Exposure (kt-yr.)
IMB	3.3	12.1 (I, II, III)
Kamiokande	0.8–0.9	4.9 (I, II)
KGF	0.06–0.16	0.8 (I, II)
Frèjus	0.55	1.6
Soudan II	0.8	not yet published
Super-Kamiokande	22.0	under construction

3.1 The Standard Model Framework

In the Standard Model, interactions between the elementary fermions are mediated by three forces: electromagnetism, the weak force, and the strong force. These forces arise from fundamental local gauge symmetries of nature, as represented in the form of the covariant derivative:

$$D_\mu = \delta_\mu - ig_1\frac{Y}{2}B_\mu - ig_2\frac{\tau^j}{2}W^j_\mu - ig_3\frac{\lambda^a}{2}G^a_\mu.$$

Each of the three gauge terms is characterized by a (multicomponent) vector field (B, W, or G); an internal symmetry structure [with generators Y for U(1), τ for SU(2), and λ for SU(3)]; and a scalar coupling constant (g_1, g_2, and g_3).

The vector fields correspond to spin-one bosons (one for each degree of freedom in the internal space) which mediate the interactions between the fundamental fermions (i.e., quarks and leptons). Parity violation in weak interactions is introduced by having the SU(2) term act only on left-handed fermions (arranged in doublets) and not on right-handed fermions (arranged in singlets), and also by assuming a different Y for the left- and right-handed states. Parity conservation is restored in electromagnetic interactions when the W^0 and B fields mix to form the γ and Z fields. It is this framework of electroweak mixing that has served as a blueprint for more extensively unified models which predict nucleon instability.

Though the W and Z have been found at the predicted masses, a true confirmation of the Standard Model (complete with Higgs mechanism) would be the discovery of the physical Higgs boson. This would also shed light on the nature of the fermion-Higgs couplings. Hopefully, this will happen within the next decade at next-generation accelerators, though there is no guarantee that the Higgs will be within their range of sensitivity. Lack of any direct experimental evidence for the Higgs mechanism is a most serious hole in the Standard Model.

Nucleon instability is a natural consequence of models which attempt to extend the Standard Model to unify the strong and electroweak forces. In almost all models, the Higgs mechanism is invoked to give the intermediate vector bosons of the theory (which can mediate proton decay) a very large mass. In supersymmetric (SUSY) models, the Higgs particles can themselves mediate nucleon instability, giving, in general, different favored decay modes. Thus, discovery of proton decay could provide experimental evidence for an operable Higgs mechanism and help fill the experimental void that exists in support of this central feature of electroweak unification and the Standard Model.

The success in explaining much of the character of low-energy particle interactions by describing them in terms of local gauge symmetries (each with its own gauge coupling parameter and vector boson multiplet) leads naturally to the question of why these specific separate symmetries are the ones nature has selected to be respected. Perhaps they are part of a larger local gauge symmetry. Supporting such a hypothesis is the fact that the individual coupling constants of the Standard Model have an energy dependence, governed by the renormalization group equations, which cause them to evolve in such a way as to converge somewhere in the energy region of 10^{15} GeV.

There are good theoretical reasons to believe that protons might decay into lighter particles. Firstly, there is no *fundamental gauged* symmetry in the Standard Model associated with either baryon number or lepton number which would lead to their conservation, thus ensuring proton stability. Secondly, the observed baryon asymmetry of the universe (i.e., more matter than antimatter) implies that baryon number is not conserved at some level, if one makes the assumption that the Big Bang baryon number of the universe was zero. Thirdly, in many SUSY theories, there are scalar Higgs particles which can mediate proton decay; thus the proton lifetime may be measurably short, even if the GUT energy scale is so high as to virtually exclude vector-boson mediated decay.

Under SU(5), it was possible to make a relatively accurate prediction of the proton lifetime and branching ratios.[3] The proton mean lifetime was predicted to be $10^{29 \pm 2}$ years with the dominant branching ratio being to the lightest lepton and meson, $e^+\pi^0$. This prediction was ruled out by the first results from IMB in 1983. Current results from IMB set a lower limit on this decay lifetime divided by a branching ratio of 8.4×10^{32} years. The possibility of grand unification gains credence in light of recent LEP experiments which have allowed for new determinations of M_Z, α_s, and $\sin^2 \theta_W$ leading to much more precise measurements of electroweak and strong coupling constants at the M_Z scale. As shown by Amaldi *et al.*,[1,2] the LEP measurements have allowed for more conclusive extrapolations to high energies in search of the unification scale. It was found that in a nonsupersymmetric Standard Model with only one Higgs doublet, the convergence of coupling constants at a single point is excluded by more than eight standard deviations (see Fig. 2). With additional Higgs doublets, unification can be obtained; however, this unification is at a scale conflicting with the experimental limits on the nucleon lifetime.

The results from LEP, coupled with limits on nucleon stability, demonstrate that the idea of a single-point unification of the coupling constants is too simple-minded and stands in need of correction. Either there is no desert between the electroweak and GUT mass scale or GUT is broken in several steps. Since 1986, other GUT models have produced a broad range of possible nucleon lifetimes. Nevertheless, the recent precise LEP measurements now confine the nucleon decay lifetime range for many models to a region just above and close to the current experimental limits.

Figure 2. Evolution of the three coupling constants: (a) in the minimal Standard Model using M_Z and $\alpha_s(M_Z)$ from world averaged data, (b) in the minimal SUSY model (M_{SUSY} has been fitted by requiring crossing of the couplings in a single point). Figure taken from paper by U. Amaldi *et al.*[2]

The inconsistency of the minimal SU(5) model with the observed values of $\sin^2 \theta_W$ and the lower limit on proton lifetime brings forward some new features related to the probing of grand unification through proton decay. To begin with, this inconsistency must not, of course, be interpreted as evidence against the basic idea of grand unification. This is because, as pointed out by several authors[1−6] beginning in the 1980s (in fact, prior to the recent observations), some well-motivated extensions of minimal SU(5) lead to values of $\sin^2 \theta_W$ and τ_p which are higher than those of minimal SU(5), both in accord with the recent data.

In the supersymmetric extension of the Standard Model with a minimal Higgs sector of two doublets, a single convergence point is obtained in the extrapolations of the running coupling constants measured at LEP by fitting both the unification scale M_{GUT} and the SUSY breaking scale M_{SUSY} (Fig. 2). For the fitted value of $M_{GUT} = 10^{15.8 \pm 0.3 \pm 0.1}$ GeV, the nucleon lifetime was estimated to be □$10^{34.5\pm1.2}$□years, if the decay is dominated by gauge boson exchange. This is within the 10^{34}□year sensitivity of Super-Kamiokande, though the entire "vector-boson-only" range is not completely covered.

3.2 Current Experimental Status

Although candidate nucleon decay events have been observed, no experiment has yet found evidence for nucleon decay above the expected neutrino backgrounds. The recent generation of detectors has included two types: fine-grain tracking calorimeters and very large water Cherenkov detectors. For nearly every decay mode examined, these detectors (IMB and Kamiokande) have placed the most stringent limits on the nucleon lifetime. This section provides a brief summary of the current status; more detailed reviews of the recent results can be found in Refs. 7 and 8. The results presented here for IMB-3 are preliminary as analysis of the final IMB data continues.

The decay mode that has received the most attention, both theoretical and experimental, is $p \to e^+\pi^0$. The most recently published result from IMB on this decay mode[9] was based on data through 1988 covering 376 days of IMB-3 livetime. It set a partial lifetime limit for $p \to e^+\pi^0$ of 5.5 x 10^{32} years at a 90% confidence level when data from the IMB-1 detector are included. Since then, an additional 448□days of data in IMB-3 have been accumulated. Preliminary analysis of this sample indicates that there is no $p \to e^+\pi^0$ decay candidate. These accumulated data in IMB restrict the proton's lifetime into this decay mode to be at least 8.4 x 10^{32} years. Neither the Kamiokande nor the Frèjus experiments have observed a candidate for this mode. Thus, a combined lower limit on the partial lifetime based on the world's data is 1.2 x 10^{33} years.

Supersymmetric unified theories tend to favor the decay mode $p \rightarrow \nu K^+$. Kaons resulting from proton disintegration would decay at rest either to $\nu\mu^+$ (63%) or $\pi^0\pi^+$ (21.2%). For the kaon decay into $\nu\mu^+$, four candidates with compatible muon energy were found in a subset of the IMB-3 data. Without subtracting background, these four events imply a lower limit to the partial proton lifetime of $\tau_B \geq 1.0 \times 10^{31}$ years. The $K^+ \rightarrow \pi^0\pi^+$ channel, though with a small branching ratio, produces more light due to the two γ's from the π^0 decay; the presence of the π^+ is inferred by detection of the delayed μ^+ decay. Two events were found to be compatible with this decay mode in IMB-3 data; however, each event had a collapsed Cherenkov ring indicating the presence of a recoil proton as expected from a neutrino interaction. Thus there are no $p \rightarrow \nu K^+$, $K^+ \rightarrow \pi^0\pi^+$ candidates so the proton's partial lifetime must be $\tau_B \geq 5.7 \times 10^{31}$ years. Preliminary analysis of more data increases the limit to 8.3 x 10^{31} years. The current Kamiokande lower bound for the $p \rightarrow \nu K^+$ decay mode is 1.0 x 10^{32} (five candidates), and the Frèjus limit is 0.15 x 10^{31} with one candidate. These candidates are all compatible with the expected neutrino background so there is no evidence for supersymmetric nucleon decay.

A general analysis that works for all nucleon decay modes begins by noting that a nucleon that decays does so nearly at rest. The daughter particles should have a total energy of about 1 GeV and should be emitted to balance their momentum. However, a particle's energy that is visible in a detector, especially a Cherenkov detector, is often less than its total energy. The total visible energy is the quantity of interest for each event. A parameter known as anisotropy, defined as the normalized average direction of the flow of visible energy in each event, is used to estimate the degree of momentum imbalance in the event; the anisotropy should be near zero for a well-balanced back-to-back event and near one for an event with a single visible track. Detailed simulations of the particle's interactions in the detector and the detector's response are required to determine the range of parameters possible for each nucleon decay mode of interest. The results of this preliminary analysis are presented in Table 4. Results for a variety of modes from IMB-1 and IMB-2 are found in Refs. 10 and 11.

Table 4. Selected nucleon decay partial lifetime lower limits (90% C.L.) set by IMB using visible energy and anisotropy cuts. Also given is the best limit from the other nucleon decay experiments.

Mode	τ/Br IMB-3 ($x10^{31}$ yr.)	τ/Br IMB-1+2 ($x10^{31}$ yr.)	τ/Br Other Expts. ($x10^{31}$ yr.)
$p \to e^+k^0$ ($K^0_s \to \pi^0\pi^0$)	11	8.3	20
$p \to e^+k^0$ ($K^0_l \to \pi^0\pi^0\pi^0$)	6.1		
$p \to e^+\eta$ ($\eta \to$ *neutrals*)	16	20	14
$p \to e^+\eta$ ($\eta \to$ *charged*)	2.9		
$p \to e^+\rho$	3.0	3.2	7.5
$p \to e^+\omega$ ($\omega \to \pi^+\pi^-\pi^0$)	11	5.6	4.5
$p \to e^+\omega$ ($\omega \to \pi^0\gamma$)	1.8		
$p \to e^+\gamma$	20	46	13
$p \to \mu^+\pi^0$	16	27	23
$p \to \mu^+K^0$ ($K^0_l \to \pi^0\pi^0\pi^0$)	11	7.6	12
$p \to \mu^+K^0$ ($K^0_s \to \pi^+\pi^-$)	7.6		
$p \to \mu^+K^0$ ($K^0_s \to \pi^0\pi^0$)	0.4		
$p \to \mu^+\eta$ ($\eta \to$ *neutrals*)	13	8.0	7
$p \to \mu^+\eta$ ($\eta \to$ *charged*)	1.4		
$p \to \mu^+\mu^+\mu^-$	17	21	20
$p \to e^+e^+e^-$	31	51	50
$n \to \nu K^0$	1.4	2.4	8.6
$n \to \nu\eta$	4.1	4.5	5.4
$n \to \nu\omega$ ($\omega \to \pi^+\pi^-\pi^0$)	1.8	20	4.3
$n \to \nu\omega$ ($\omega \to \pi^0\gamma$)	0.5		

For some decay modes, it is possible to make a more discriminating selection of nucleon decay candidates by deducing the invariant mass and residual momentum of the particles in the event. This is possible for those events with widely separated tracks because then each track's momentum can be unambiguously measured. Table 5 shows preliminary results, based on a subset of the IMB-3 data, using this analysis for some selected decay modes. The candidates are located among the wide angle two-prong events that constitute a small fraction (~ 3%) of the data sample. For the selected events, invariant masses and residual momenta are calculated assuming all possible particle hypotheses for each track. This analysis usually has slightly poorer efficiency due to the stringent requirements on the track identification; however, in reducing the measured (and expected) neutrino background, it often produces better limits on the nucleon's partial lifetime.

Table 5. Nucleon decay partial lifetime lower limits obtained with the invariant mass analysis from IMB-3.

Mode	No. of Candidates	No. of Bkgd.	τ/Br IMB-3 (x 10^{31} yr.)	τ/Br IMB-1+ 2 (x 10^{31} yr.)	τ/Br Other Expts. (x 10^{31} yr.)
$p \to \mu^+\gamma$	0	0.2	25	38	16
$n \to e^+\pi^-$	0	0.4	4.8	10	13
$n \to \mu^+\pi^-$	2	0.7	4.6	6.3	10
$p \to \mu^+\omega$	1	0.6	1.6	4.2	5.7
$p \to \mu^+\rho$	3	1.5	4.1	3	12

There is currently no compelling experimental evidence for nucleon decay above expected neutrino backgrounds into any mode tested so far. On the other hand, many of the decay modes in question remain background free or nearly background free. Therefore, there is a clear need for a much larger detector with improved resolution to continue the search. The preceding section showed that there are sound theoretical reasons to expect that the proton is not absolutely stable. Current unified theories predict the exciting possibility that the proton's lifetime may be well within the discovery potential of Super-Kamiokande.

3.3 Sensitivity of Super-Kamiokande

In their searches for nucleon decay over the last decade, the two largest detectors have collected data corresponding to a total exposure of 17.7 kt-yr (kiloton-years): 11.5 kt-yr for IMB and 6.2 kt-yr for Kamiokande. According to a preliminary analysis of the total IMB sample plus a 3.76 kt-yr sample of Kamiokande data, no candidate for a $p \to e^+\pi^0$ decay was found; this yields a lower bound on the proton lifetime of 1.1×10^{33} B years, where B is the branching ratio into this particular decay mode. In five years of running, Super-Kamiokande will achieve an exposure of 110 kt-yr. This will correspond to a sensitivity to ~10^{34} years for the decay modes which give clear signals above the atmospheric neutrino background.

IMB-3 observed atmospheric neutrino interactions in contained events at a rate of 121 ± 4 (stat) kt-yr^{-1} and Kamiokande II in fully contained events of 87 ± 6 (stat) kt-yr^{-1}. Our Monte Carlo estimates that the events observed in IMB-3 constitute 69 ± 7% (syst) of all the atmospheric neutrino interactions which produce particles detectable by the water Cherenkov technique. This leads to an estimate of 176 detectable interactions occurring in water per kt-yr. This estimate is free of uncertainties in the neutrino fluxes and total cross sections, but is subject to an uncertainty of ~ 10% in the IMB-3 experimental event-saving efficiency estimate.

It can be conservatively estimated that the neutrino background for $p \to e^+\pi^0$ is less than 0.1 event per year (90% C.L.) of Super-Kamiokande livetime. Assuming an overall event-saving efficiency of 60%, one can get a lower bound on $\tau_B \geq 1 \times 10^{34}$ years if no candidate is found after five years of livetime or 1.9 times lower if one candidate is found. The expected sensitivities of the Super-Kamiokande experiment to other interesting nucleon decay modes are presented in Fig. 3. The published experimental lower limits on the nucleon lifetime are also shown. Table 6 shows the current lifetime limits for several representative two-body decay modes while Table 7 shows similar numbers for two-body decay modes with a neutrino in the final state. Included in both tables are estimates of the sensitivity which could be reached by Super-Kamiokande after several years of operation.

Figure 3. The expected sensitivities of the Super-Kamiokande experiment to various interesting nucleon decay modes are indicated by hatched areas. The lower limits on the nucleon lifetime from various experiments are shown as indicated in the legend.

Table 6. Current proton decay partial lifetime lower limits for some representative two-body modes compared with the sensitivity expected for Super-Kamiokande.

Decay Mode	90% C.L. Upper Limit ($\times 10^{31}$ yr.)	Detector
$p \rightarrow e^+\pi^0$	84 26 1000	IMB Kamiokande Super-Kamiokande
$p \rightarrow e^+\eta^0$	20 14 600	IMB Kamiokande Super-Kamiokande
$p \rightarrow e^+\omega^0$	11 4.5 90	IMB Kamiokande Super-Kamiokande
$p \rightarrow e^+\rho^0$	3.2 7.5 90	IMB Kamiokande Super-Kamiokande
$p \rightarrow e^+K^0$	11 15 100	IMB Kamiokande Super-Kamiokande
$p \rightarrow \mu^+\pi^0$	27 23 1000	IMB Kamiokande Super-Kamiokande
$p \rightarrow \mu^+\eta^0$	13 6.9 600	IMB Kamiokande Super-Kamiokande
$p \rightarrow \mu^+K^0$	11 12 300	IMB Kamiokande Super-Kamiokande
$p \rightarrow \mu^+\rho^0$	4.1 11 90	IMB Kamiokande Super-Kamiokande
$p \rightarrow \mu^+\omega^0$	4.2 5.7 90	IMB Kamiokande Super-Kamiokande

Table 7. Current partial lifetime lower limits for modes with a neutrino in the final state compared with the capability of Super-Kamiokande.

Decay Mode	90% C.L. Upper Limit ($\times 10^{31}$ yr.)	Detector
$p \to \nu\, \pi^+$	2.5 60	Kamiokande Super-Kamiokande
$p \to \nu\, \rho^+$	1.4 2.7 60	IMB Kamiokande Super-Kamiokande
$p \to \nu\, K^+$	5.7 10 100	IMB Kamiokande Super-Kamiokande

4. Atmospheric Neutrinos

While atmospheric neutrinos present a background to some physics searches (e.g., proton decay and extraterrestrial neutrino astronomy), they are a rich source of physics in their own right. The atmospheric flux covers a broad range of neutrino energies from tens of MeVs to tens of TeVs and beyond. These neutrinos travel distances from 10 km to 10,000 km. This section will briefly discuss the current status of atmospheric neutrino studies.

4.1 Theoretical Situation

Atmospheric neutrinos are generated in cosmic ray interactions in the atmosphere. A cosmic ray (either proton or nucleus) interacts producing a cascade of secondaries; the secondaries (typically pions and kaons) may either interact again or decay. This cascade continues until the primary's energy is dissipated in the atmosphere, primarily by ionization.

Some approximate predictions can be made from this simple picture.[12] The first is that the neutrino energy spectrum will follow the power-law primary spectrum. In such a cascade, the number of positively charged secondaries will be nearly equal to the number of negatively charged secondaries. Thus, if we assume that all low-energy pions decay,

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu\,,$$

and that their muon secondaries also decay,

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu,$$

simple counting of the daughters allows the conclusion that

$$(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e) \approx 2/1 \quad \text{and} \quad (\nu/\bar{\nu}) \approx 1/1.$$

These estimates are born out by the sophisticated Monte Carlo calculations of the atmospheric flux.

With the advent in the 1980s of new underground detectors designed for proton decay searches, it was necessary that refined calculations of the atmospheric neutrino flux and spectrum be made. In particular, it was necessary to extend the calculations to lower neutrino energies; at high energies, (semi-) analytic calculations can be used. The new calculations were needed to accurately describe the physics that occur in the cascade over a very broad energy range and is difficult to model analytically. Physical processes, such as kaon production or resonance formation in pion interactions, must be included. Thus, rather sophisticated Monte Carlo simulations were made by several different groups. As with any calculation of a secondary neutrino beam, the atmospheric neutrino calculations have various uncertainties. Some of these, such as the composition and flux of the primary cosmic rays, are common to all of the calculations. Other uncertainties, for example, the physics assumptions in the interaction model, are not common to the different calculations. It is estimated that the total uncertainty in the absolute neutrino flux calculation is about 20%.

At low neutrino energies (100 MeV–10 GeV), three different calculations of the expected flux and spectrum have been performed.[13] While a detailed comparison of the results from these calculations is beyond the scope of this paper, a few remarks are in order. The different calculations predict absolute neutrino rates that vary by about 30% in the extreme. However, the predicted relative rate of electron- and muon-neutrino interactions varies by only a few percent. Table 8 illustrates this point; using the different neutrino calculations, the absolute number of events predicted in IMB-3 varies substantially, while the predicted fraction of events that are identified as muon-neutrino interactions does not vary. This is because both the predicted muon- and electron-neutrino fractions and the predicted shape of the neutrino energy distributions are very similar in all calculations.

Table 8. Comparison of the absolute rate of single-ring events in IMB-3 within a restricted particle momentum range for various authors' flux calculations.

Flux Calculation	ν_μ-like rate (day^{-1})	Fraction	ν_e-like rate (day^{-1})	Fraction
Lee	0.31	0.51	0.30	0.49
Gaisser	0.40	0.50	0.40	0.50
Honda	0.35	0.51	0.34	0.49

At higher energies (10 GeV–10 TeV), four different calculations have been made.[14] Because at high energies the model of particle interactions is simpler, analytic and semianalytic calculations can be used (e.g., Volkova, Butkevich) as well as Monte Carlo based calculations. Like the lower energy calculations, the high-energy calculations have common uncertainties. Additionally, because these high-energy events are observed as neutrino-induced muons entering the detector from below, other uncertainties, such as the nucleon's structure function and the muon's propagation and energy loss in rock, become important. Thus, again the absolute rate of entering neutrino-induced muons is quite uncertain, this time by about 25%; however, since the neutrino energy spectrum is much better determined, the fraction of those muons that stop in the detector is well-calculated.

4.2 ν_μ and ν_e Separation

The flavor of the parent neutrino is determined by identifying the lepton type produced in the interaction. Two methods have been used to discriminate between electron- and muon-neutrino induced events: the first is to observe the muon's decay and the second is to examine in detail the nature of the particle tracks.

The first, and conceptually the simplest, method is to record muon decays that occur after the event in question. (Not all detectors have the ability to recognize the low energy electrons from stopped muon decay.) If the muon decays can be recorded, this method can help distinguish between events with and without a muon. However, this method may suffer from some deficiencies. Negative muons can be captured and therefore be lost. In addition, a pion in an event can decay, producing a muon whose delayed decay is then observed. Thus, neutral current events, due to either electron- or muon-neutrinos that produce pions, can appear to be muon-neutrino induced.

The second method is more efficient but also more complicated. This pattern recognition approach in water Cherenkov detectors utilizes the difference between an electron's showering track and a muon's minimum ionizing track as these particles pass through the detector. This method can also be fooled by pion production in neutral current events; however, some detectors have the ability to identify and discard such events.

4.3 Experimental Results

As described above, neutrinos produced in the atmosphere by cosmic ray interactions give rise to two types of recorded events in large underground detectors: contained and external (or entering).

Atmospheric electron- and muon-neutrinos of average energy ~ 1 GeV, which interact within the detector volume, produce contained events. Contained event rates, which depend on the energy threshold and geomagnetic latitude of a detector, as well as solar activity, are typically 0.5 kt^{-1} d^{-1}.

Atmospheric muon neutrinos of energy ≥ 4 GeV, which make muons via charged current interactions in the Earth surrounding the detector, produce external events. Muons from external events enter the detector from all directions. Because of the abundant flux of atmospheric muons entering the detector from above the horizon, only upward-going external events can be reliably attributed to atmospheric muon neutrinos. Upward-going muon event rates, which depend primarily on a detector's muon energy threshold, are typically 0.3–0.4 m^{-2} yr^{-1}.

4.4 Recent Results (E_ν ~ 1 GeV)

This section reviews recent results on contained events. A more detailed discussion can be found in Ref. 15. Large samples (> 100) of contained events have been collected by two general types of detectors. The rates have been consistent with the expected interactions of atmospheric neutrinos. Because no conclusive evidence for nucleon decay has yet been observed, these samples have been wholly attributed to atmospheric neutrinos. The possibility that events from other sources have been observed cannot be excluded, however, due to the large uncertainty (± 20%) in the prediction of the absolute rate of atmospheric neutrino-induced events, as discussed above.

One class of detectors is ring-imaging water Cherenkov detectors. They provide the largest samples of atmospheric neutrino-induced events. These massive detectors employ water both as an inexpensive target material and the detection medium. They use many photomultiplier tubes to sample Cherenkov radiation produced by relativistic charged particles. Water Cherenkov detectors operate as total absorption calorimeters. Massive particles, such as $\mu^{\pm}$ and $\pi^{\pm}$, must be above Cherenkov threshold (~ 180 MeV/c) to be detected. Reliable discrimination between massive and showering ($e^{\pm}$, γ) particles is possible with sufficient Cherenkov light collection (≥ 1 pe/MeV). Particle direction is unambiguous but vertex resolution is relatively poor (~1 m).

Small samples of contained events are available from iron tracking calorimeters. These neutrino detectors require volume-intensive instrumentation, limiting their size, but providing excellent spatial resolution (~ 1 cm) and reconstruction of particle tracks. Particle types are inferred from their range and ionization yield. A particle's direction is often not determined in these detectors.

4.5 Results from IMB

The IMB-1 detector recorded 401 contained events during an exposure of 3.77 kt-yr extending from September 1982 to June 1984. These data provided an early measurement of the atmospheric neutrino spectrum and composition.[16] The fraction of events having an identified muon decay, which indicates the content of muon- and neutrino-induced events in the sample, was 26% ± 3%. Simulated data predicted 34% ± 1%. This was the first reported indication of a possible problem with the atmospheric neutrino flavor composition. Separation of single- and multiple-ring events and identification of particle types in IMB-1 was not efficient enough to warrant more sophisticated analyses of flavor composition.

The IMB-3 detector began operation in May 1986 after an upgrade in sensitivity to Cherenkov light. The added light collection allowed more efficient detection of muon decay, a lower trigger threshold, separation of single- and multiple-ring events, and particle identification. By March 1991, an additional 935 contained events were collected during an exposure of 7.7 kt-yr. These data provided a more precise measurement of the atmospheric neutrino spectrum and particle content.[17] The muon decay fraction of this sample was 37% ± 2%. Simulated data based on an independent model of the atmospheric neutrino flux predicted 44% ± 1%. The muon decay deficiency suggested in IMB-1 data was also seen in the IMB-3.

A more sensitive test of the neutrino flavor composition in the atmospheric flux differentiated between nonshowering and showering particles (in single-ring events) using a pattern recognition method. These results confirmed an apparent deficit of muon neutrinos interacting in the detector. The number of nonshowering, single-ring events, as a fraction of the total number of single-ring events, in IMB-3 was 36% ±□2□% (syst) ± 2% (stat). The prediction, based on simulated data, was 51% ± 5% (syst) ± 1% (stat). Again, a shortage of muon-neutrino induced events was apparent (see Fig.□4).

Figure 4. Momentum distribution of showering and nonshowering events observed in the IMB-3 detector.

4.6 Results from Kamiokande

The Kamiokande detector has collected 557 events in 6.18 kt-yr of exposure.[18] Although smaller than IMB, its resolution is better and its energy threshold is lower due to a greater sensitivity to Cherenkov light. A subset of these data were the first to be analyzed using single-ring event separation and particle identification by pattern recognition. Similar deficits of muon decays and ν_μ-induced events are observed in the Kamiokande data. They observe a fractional rate of nonshowering events of 49% ± 4% while they expect 61%. Table 9 compares the IMB-3 and Kamiokande data.

Table 9. Summary of contained events from IMB-3 and Kamiokande.

	IMB-3 # Evts.	IMB-3 Fract. of Total	Kamiokande # Evts.	Kamiokande Fract. of Total
Observed 1-Ring	507	-	310	-
Monte Carlo 1-Ring	525	-	333	-
Observed μ Decay	168	0.33	112	0.36
Monte Carlo μ Decay	223	0.43	162	0.49
Obs./MC μ Decay	-	0.77 ± 0.06	-	0.73 ± 0.07
Observed e-like	325	0.64	159	0.51
Monte Carlo e-like	257	0.49	128	0.38
Observed μ-like	182	0.36	151	0.49
Monte Carlo μ-like	268	0.51	205	0.62
Obs./MC μ-like	-	0.71 ± 0.05	-	0.79 ± 0.06

4.7 Results from the Frèjus Experiment

The Frèjus detector collected 188 events.[19] All events with visible energy greater than 200 MeV and an identified lepton are used to measure the ratio of charged current events due to electron- and muon-neutrinos. Neutral current events are identified in this analysis. These data do not show a deficit of ν_μ-induced events. They measure a fraction of muon-neutrino induced events, compared with the expected 1.0 ± 0.1. On the other hand, the number of events recorded in Frèjus is not sufficient to conclude that these data are in disagreement with that from IMB and Kamiokande. Furthermore, the Frèjus trigger efficiency is ~ 50% at 500 MeV, which is a much higher threshold than in the water Cherenkov detectors. The lower energy data, called fully contained events by the Frèjus collaboration, exhibit a slight deficit of muon-neutrino induced events, though statistically consistent with their overall result.

4.8 Results for $E_\nu \sim 100$ GeV

External events can be used to monitor the flux of atmospheric ν_μ at energies typically 100 times higher than that of contained events. The direction of an upward-going muon is well correlated with that of its ν_μ parent. The distribution of zenith angles, which peaks at the horizon due to the increased decay length in the atmosphere, is sensitive to possible distortions due to neutrino oscillations. The detectors provide limited information on the energy spectrum of external events, thus limiting the deduced information on the neutrino spectral shape. Large samples of external events have been collected by three experiments. Two are the large ring-imaging water Cherenkov detectors mentioned above. The other is a telescope constructed of scintillation counters (Baksan). The IMB detector recorded 617 upward-going muon events during an exposure of 1444 m^2 yr. This corresponds to a flux of 2.54 ± 0.10 (stat) x 10^{-13} $cm^{-2}s^{-1}sr^{-1}$ above a muon energy threshold of ~1.2□GeV. The predicted value, which is based on a hybrid of the Volkova and Lee and Koh flux models, is 2.46 ± 0.49 (syst) x 10^{-13} $cm^{-2}s^{-1}sr^{-1}$. Information about the neutrino energy spectrum is provided by measuring the fraction of upward-going muons which stop inside the detector. The measured stopping fraction is 0.138 ± 0.014 (stat), while simulations predict 0.140 ± 0.005 (stat).

4.9 Possible New Physics: Neutrino Oscillations

One obvious explanation of the apparent dearth of muon-type events is neutrino flavor oscillations. Oscillations between neighboring neutrino families is theoretically preferred. Muon-neutrino to tau-neutrino oscillations will most effectively rid the observed atmospheric neutrino events of a muon-like component; however, $\nu_e \rightarrow \nu_\mu$ oscillations are also possible. Recently, this issue was addressed[15] in detail. Based on the assumption that ν_μ's disappeared into tau-neutrinos (that do not make a visible interaction at these energies), the postulated parameters ($\sin^2 2\theta$ and δm^2) were used to predict the oscillated composition observed in the detector. See Ref. 18 for the oscillation allowed region of $\sin^2 2\theta$ and δm^2.

While the case can be made for neutrino oscillations as the solution to the atmospheric neutrino problem, this explanation is not without its own deficiencies.

More convincing evidence for neutrino oscillations would be found in either the observed neutrino energy spectrum (low energy neutrinos oscillate earlier) or in their zenith angle distribution (downward-going neutrinos may not have had a chance to oscillate due to their short path length); however, there is no statistical evidence that the observed deficit of muon-like events depends on either zenith angle or energy. These dependencies are not required but would have provided proof that oscillations were observed.

Further, the upward-going external muon-neutrino induced events would most likely show evidence for oscillations. Although at higher energies, these neutrinos have all traveled great distances. Yet, the rate, zenith-angle, and energy distribution of these events are as expected from predictions.[20] These facts place limits on the possible neutrino-oscillation parameters. The available parameter space left ranges from about 3×10^{-3} to 3×10^{-1} eV^2 in δm^2 and from 0.4 to 0.8 in $\sin^2 2\theta$.

4.10 Atmospheric Neutrinos in Super-Kamiokande

The size of Super-Kamiokande is very important for refined measurements of the atmospheric neutrino flux and composition. The IMB detector recorded about one contained atmospheric neutrino event/day of operation whereas Super-Kamiokande will record about seven. Systematic uncertainties will dominate the statistical uncertainty in Super-Kamiokande but the improved statistics will allow the data to be cut into different classes for systematic studies. However, it is not only size that separates Super-Kamiokande from the previous generation of underground detectors. The pattern recognition method of particle identification now suffers due to modest light collection (about 1–5 p.e./MeV) and vertex resolution (~ 1 m). Thus, the efficiency for correct particle identification in IMB-3 was slightly better than 90% and in Kamiokande it is about 98%. The enhanced light collection (7 p.e./MeV) and improved vertex resolution (~ 0.1 m) will mean the particle identification efficiency will be greater than 99%. Other properties of Super-Kamiokande are important for the study of atmospheric neutrinos. The muon decay detection efficiency, for μ^+, in IMB-3 was about 80% and in Kamiokande it is 87%. However, the faster electronics, better light collection, and lower energy threshold in Super-Kamiokande will allow a μ^+ decay to be identified 95% of the time. This will mean that this simple method of determining the particle identification will be about as efficient as the current pattern recognition methods.

5. Conclusion

Recent developments in the quest for grand unification are encouraging for experimental searches for nucleon instability. Unification is expected in an energy region which implies a nucleon lifetime close to the values being currently probed. Theory, however, does not provide us with any definite guideline about a preferred decay mode. Depending on the unification model, the dominant decays may lead to a lepton and a pion or to a neutrino and a kaon. It is clear that the relatively small coverage of light sensors in IMB restricted the quality of our results for those decay modes where a better Cherenkov image of a massive particle with low velocity would be vital. This applies to all the decays leading to charged pions in the final state. Even if a pion is produced at relatively high energy, as in two-body decay modes, the nuclear interactions inside the oxygen nucleus and during its passage through water decrease its final light output.

Some decay modes, e.g., $p \rightarrow e^+\pi^0$, are still easily selected from the background. We expect less than 0.1 background events/year for $p \rightarrow e^+\pi^0$ decay. In order to probe the broadest possible range of expected nucleon partial decay rates for the background-free modes, the increase in the fiducial volume and detection livetime represented by Super-Kamiokande is vital. However, for most decay channels, an effective background rejection becomes of major importance. It is seen in the tables presented earlier that very few decay modes have zero candidates. Due to the soft spectrum of atmospheric neutrinos, many recoiling protons, as well as many charged pions, remained invisible with the IMB detector light sensitivity. The observation of images from particles just above their Cherenkov thresholds will greatly reduce the number of events considered as candidate nucleon decays.

Better energy resolution will also improve the signal to background ratio. The invariant mass analysis would be more effective in selecting the potential nucleon decay candidates from the continuous neutrino interaction background. An improved energy resolution is essential for identifying monoenergetic muons of 236 MeV/c momentum that unambiguously signal a decay of a kaon resulting from any (p or n)$\rightarrow$ lepton + K^+ decay. A unique identification of kaons is particularly interesting because they are very unlikely products of the soft atmospheric neutrino interactions. Super-Kamiokande will have better energy resolution than either IMB or Kamiokande due to its increased light collection and ability to calibrate efficiently from low-energy electrons. In conclusion, there are strong theoretical and experimental motivations to extending the nucleon decay searches begun in the 1980s by IMB and Kamiokande.

The underground measurements of the atmospheric neutrino spectrum and composition are in good agreement. The disagreement between these measurements and the theoretical predictions is, however, statistically quite significant. The cause of the disagreement must thus be either an unidentified systematic effect in the flux calculation, neutrino model, or detector simulation, or some new physics.

Investigation of systematic effects (the neutrino model or detector simulation) requires controlled experiments. Such experiments include a charged particle beam test and a future neutrino beam test. Both of these tests use a large water Cherenkov detector at KEK. Isolation of potential systematic problems with the neutrino flux calculations will require, among other things, much more atmospheric neutrino data to search for energy, zenith angle, or other effects that might indicate the nature of the problem.

The unambiguous confirmation that the atmospheric neutrino problem is the result of some exciting new physics will require a vast increase in the size of the neutrino event sample. The most compelling explanation involving new physics is that neutrino oscillations are causing the ν_μ's to disappear before they reach the underground detectors. Several complimentary approaches are likely to be required to completely probe this possibility. One approach would use the greater statistics in the neutrino sample, along with greatly improved resolutions and particle identification efficiencies of Super-Kamiokande, to allow a detailed systematic search for possible energy or path-length deviations that would indicate neutrino oscillations.

Another approach that will be used to attack this problem will be accelerator-based, long-baseline neutrino oscillation experiments. Because of the range of neutrino masses implied by the atmospheric anomaly, such an experiment will require that the neutrino beam energy and path length satisfy $L/E \geq 100$ km/GeV. Such possibilities are being investigated in proposals at FNAL, BNL, and CERN for long-baseline neutrino experiments. A ~ 1 GeV neutrino beam from KEK pointed at Super-Kamiokande would fulfill this requirement with the added advantage of using an existing, well-understood, very large detector with excellent resolution. Super-Kamiokande provides a unique opportunity to study atmospheric neutrinos in detail.

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