History of “Anomalous” Atmospheric Neutrino Events: A First Person Account*†

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Abstract

The modern picture of the neutrino as a multiple mass highly mixed neutral particle has emerged over 40 years of study. Best known of the issues leading to this picture was the apparent loss of neutrinos coming from the sun. This article describes another piece of evidence that supports the picture; the substantial reduction of high energy muon type neutrinos observed in nature. For much of the 40 year period, before the modern picture emerged this observation was known as the “atmospheric neutrino anomaly”, since as will be seen, these neutrinos originate in the Earth’s atmosphere.

This paper describes the discovery of the atmospheric neutrino anomaly. We explore the scientific context and motivations in the late 1970’s from which this work emerged. The gradual awareness that the observations of atmospheric neutrinos were not as expected took place in the 1983-1986 period.

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Contents

Introduction ........................................... 7
Scientific Context ...................................... 8
  Solar Neutrinos ..................................... 10
Inspiration ............................................ 11
Inspiration 2 ........................................... 12
Formulation I – Accelerator Experiments .......... 15
Formulation II – Neutrinos in Nature ............... 17
Preparation ............................................ 21
Observation ............................................ 29
Interpretation .......................................... 33
Consternation .......................................... 38
Confirmation ........................................... 40
Epilogue ................................................ 42
Conclusions ............................................ 44
Thanks ................................................... 46
Acknowledgments ...................................... 46

List of Figures

  1  Title and abstract of the 1976 Mann and Primakoff paper that
     explored the possibilities of three neutrino oscillations .... 11
2 A sketch of the IMB detector which was used for much of the work described in this paper. The sketch shows the size of the cavity excavated out of salt and filled with ultrapure water. The lines and black dots represent the phototubes and cables used to read out light signals from Cherenkov light produced in the water by fast charged particles. The fiducial volume two meters in from the phototube planes is indicated by the internal rectangular solid. The fiducial mass is a bit over 3.3 kilotons.

3 An event from the Brookhaven neutrino oscillations search. The detector design was typical of the time. It was composed of a large segmented volume of liquid scintillator. The segmentation permitted the crude reconstruction of the tracks in the event. In the sample event illustrated three scintillation cells have energy deposited in them. The recoil energy and direction, as well as a knowledge of the neutrino beam direction, permitted a reconstruction of the neutrino interaction.

4 Members of a dedicated neutrino oscillations experiment at Brookhaven National Laboratory in 1977. LoSecco is on the left and Larry Sulak is kneeling on the right. Bill Wang is kneeling to the right of LoSecco. Andy Soukas is in the middle of the group of accelerator operators standing in the back.

5 The block diagram for the IMB experiment electronics. This provided an effective, accurate way to identify interactions leaving a muon in the detector. The design utilizes the approximately 2 microsecond lifetime of the muon to identify it. The electronics contained two time digitizers. The top one, labeled “Fine TAC” had a resolution of about a nanosecond and produces a measurement that is used to reconstruct the position and direction of the event. The center of the figure includes the design for a coarse time scale (labeled “Coarse TAC”), called a T2. This provided a 10 microsecond window, following a triggering interaction to observe particle decays of the products of the interaction. The rest of the electronics on the diagram provided for energy integration, and the ability to trigger the detector. A muon was identified when several phototubes gave a delayed signal following a triggered interaction.
| Page | Description |
|------|-------------|
| 6    | The title page for Sulak’s talk about the potential to observe the oscillations of atmospheric neutrinos presented at the 1980 EPS meeting in Erice, Sicily. |
| 7    | The title page for Sulak’s talk about the potential to observe the oscillations of atmospheric neutrinos presented at the 1980 First Workshop on Grand Unification (FWOGU) in New Hampshire. |
| 8    | Figures taken from the FWOGU and Erice talks illustrating the method to observe atmospheric neutrino oscillations with a detector that was already under construction to observe proton decay. The neutrino propagation distances and the neutrino energy spectrum are shown here. |
| 9    | Figures taken from the FWOGU and Erice talks illustrating the method to observe atmospheric neutrino oscillations. The neutrino energy and direction resolution are considered here. |
| 10   | The expected ratio of electron neutrino interactions to muon neutrino interactions for those neutrinos going upward and those going downward plotted as a function of the (positive) neutrino mass difference. The difference between these two samples is sensitive to neutrino oscillations over a substantial range of mass differences. |
| 11   | Heading from a 1982 internal report on calibrating the detector response to muon decays. This work was done well before the detector was completed. |
| 12   | Portions of Bill Foster’s memo of July 1983, which describes the way in which neutrino interactions were simulated in the detector. At the end of this memo he notes a discrepancy between the observed number of muon decays and the number expected based on this simulation. |
| 13   | A portion of the proceedings of the 1986 Lake Louise meeting in which I point out a discrepancy between the IMB muon observations and expectations and the reports of two other experiments. |
| 14   | The title and author list from the IMB journal article which noted the atmospheric neutrino anomaly. |
Excerpt from the 1986 IMB neutrino paper describing the atmospheric neutrino anomaly and some potential explanations. The variety of explanations represented the varied opinions of the multiple authors.  

A group photo of the IMB collaboration in 1987. The photograph was taken at a meeting in Irvine in which the observation of neutrinos from supernova 1987a was celebrated.  

Illustrations taken from the proceeding of the cosmic ray conference in San Diego in 1985. The upper part of the figure shows a neutrino oscillations exclusion region calculated based on the absence of spectral distortion in comparing the upward going to downward going neutrino events with a muon decay signature. The lower part of the figure compares the expected and observed E/L distribution for neutrino interaction in IMB-1. A problem in the -2.23 bin was noted in the text.  

IMB-3 data similar to figure 17. This figure was shown at a cosmology meeting in the Baksan Valley of the Soviet Union in 1991. The lower distribution is similar to that of figure 17 but this figure includes only events with an identified muon. In figure 17 it included all single track contained events from the earlier IMB-1 data sample.  

The atmospheric neutrino spectrum observed with Kamiokande I. The histogram data and the curve simulation are in good agreement.  

The atmospheric neutrino spectrum observed with Kamiokande I. The upper curve illustrates the good agreement for muon type events. The lower figure is for electron like events.  

The angular distribution for electron neutrinos (left) and muon neutrinos (right) reported by Kamiokande in their 1988 paper confirming the atmospheric neutrino anomaly. Note that cosine of one is for downward going events. The original caption to this figure reads “Zenith angle distributions for; (a) electron-like events and (b) muon-like events. \( \cos(\theta) = 1 \) corresponds to downward going events. The histograms show the distributions expected from atmospheric neutrino interactions.”  

Portion of handwritten notes on the event rate discrepancy between earlier Kamiokande reports and the 1988 paper confirming the neutrino anomaly.
Portion of the 1989 letter from the Kamiokande collaboration which argues that the rate difference is not significant. The 1988 paper combined data from two detectors known as Kamiokande I and Kamiokande II. Apparently the event rate per kiloton-year was expected to be lower in Kamiokande II."
Introduction

Over the last 40 years the role of the neutrino in nature has been studied and understood via observations of neutrinos from the sun, extragalactic supernovae and cosmic rays. The picture that has emerged has been corroborated by observations of neutrinos from nuclear reactors and particle accelerators. The neutrino has turned out to be a much more complicated physical system than most elementary particles. Many kinds of neutrinos and antineutrinos are now known to exist and transformations among them can now explain many of the odd features noted in the observations.

It is frequently convenient to label neutrinos by their properties under the charged current weak interaction. Under the influence of the charged current the neutrino will turn into a charged particle, a lepton. The kind of charged particle produced by the interaction is then used to label the kind of neutrino. If a negatively charged electron, muon or tau is produced the neutrino is regarded to be an electron, muon or tau neutrino. An antineutrino would produce a positively charged lepton.

Nuclear reactions in the sun produce electron neutrinos. Cosmic ray interactions in the Earth’s atmosphere produce a mixture of muon and electron neutrinos and antineutrinos.

This paper discusses the history of the discovery of what was known as the “atmospheric neutrino anomaly”. This effect is widely regarded as one of the strongest bits of experimental evidence for neutrino oscillations and hence a neutrino mass.

I will frequently use the terms neutrino mixing and neutrino oscillations interchangeably since oscillations require mixing. Neutrino mass differences are also required for the mixing to manifest itself as a time and distance dependent variation in the neutrino properties, an oscillation.

Atmospheric neutrinos are neutrinos, which are produced by cosmic ray interactions in the Earth’s atmosphere. Cosmic rays interact strongly to produce pions, kaons and other unstable particles by collision. The decay of these produced particles yields muons, the most common component of cosmic rays at ground level. The decays also produce neutrinos which, until the period involved here, were very difficult to observe [1, 2].

The atmospheric neutrino anomaly refers to the fact that the muon neutrino flux of atmospheric neutrinos is substantially lower than the expected value. It has many similarities to the solar neutrino problem, in that the neutrinos were observed in nature and the observations were well below ex-
pectation. The modern view is that the atmospheric neutrino anomaly and the solar neutrino problem are closely related via the phenomena of three flavor neutrino oscillations.

The time period of this paper is primarily 1978 to 1988. Some issues of the state of physics prior to 1978 are reviewed to set the stage for the events that followed. The early and mid 1970’s was a very productive period for particle physics. Electro-weak unification, quantum chromodynamics, grand unified theories, supersymmetry and their experimental underpinnings were all developed in this period. String theories also became well established during the 1978-1988 period of our story.

Scientific Context

Among the significant issues in neutrino physics in the mid 1970’s were a number of “discoveries” which have since been resolved and were ultimately not confirmed. Scientific discovery is rarely linear and this section describes reports that could have been central to the issue of neutrino mixing, but many of them were ultimately tangential. The goal of this section is to put the subsequent story into its historical context.

The weak neutral current is the interaction that permits neutrinos to interact without changing into a charged lepton. It is rarely relevant in nuclear and particle decays since the much stronger electromagnetic interaction can do these more rapidly. The weak neutral current was first observed in accelerator neutrino beams.

The discovery of the weak neutral current (which turned out to be true) involved considerable uncertainty[3]. This uncertainty has become known in the field as “alternating neutral currents”, since the reports of discovery came and went and then returned. In fairness to those authors one should emphasize that doing a careful job is frequently inconsistent with making a dramatic discovery. To rush such checks can lead to uncovering evidence that both supports and refutes a conclusion. As each piece of evidence is analyzed the “conclusions” may change. If one does many checks the conclusions can change many times.

The high y anomaly[4] was also a significant contributor to what would follow. This disagreement of observed kinematic distributions (the $y$ variable, the fraction of the initial neutrino energy carried by the final state muon) for (anti)neutrino interactions at high energy with expectations, was taken by
some as evidence for right handed currents. A neutrino mass would provide a natural source for right handed currents. Such currents helped motivate the possibility of neutrino oscillations in the mid 1970’s. Subsequent experiments failed to support the presence of the high y discrepancy.

Some evidence for the violation of the muon number and electron number conservation was found in the decay $\mu \rightarrow e\gamma$. The symbol $\mu$ represents the muon, $e$ the electron and $\gamma$ a gamma ray.) In such a decay muon number decreases and electron number increases but the total remains constant. The concepts of muon number, electron number and tau number had been introduced to explain the absence of transitions not forbidden by any other known conservation law. The concept declared that each of the leptons contained a unique property that was conserved in all interactions. The charged lepton and its corresponding neutrino shared this property. The concept of lepton number explains, for example why the two neutrinos produced in muon decay $\mu \rightarrow e\nu\bar{\nu}$ had to have different flavors. The decay $\mu \rightarrow e\gamma$ is forbidden since both the muon number and the electron number change by one unit.

The existence of the decay $\mu \rightarrow e\gamma$ would remove a constraint that prevented neutrinos from mixing. Ultimately the evidence for the decay $\mu \rightarrow e\gamma$ was not confirmed. Searches for this lepton number violating decay continue today.

Direct kinematic evidence for a neutrino mass was published by a Soviet group under Lubimov. Lubimov had used the classic method of studying the high energy end of the tritium beta decay spectrum with a precision spectrometer. A neutrino mass would produce distortion of the end point since a mass would limit the phase space for the highest energy electrons from this beta decay. (Their maximum kinetic energy would be lower since some of the decay energy would appear as the neutrino mass.) At the time the previous best upper bound on the neutrino mass was 60 eV using a similar method. From 1980 onward there was unrefuted evidence from this group for a neutrino mass of from 30-40 eV. It took at least a decade of effort to eventually show this result was in error. Currently there is no established value for the neutrino mass, only upper limits. Though observations do support the existence of neutrino mass differences.

A novel method of searching for neutrino flavor transformations yielded some evidence for oscillations in 1979. The concept was a good one. Use the neutral current interaction of neutrinos on deuterium to measure the neutrino flux and use the charged current interaction on the same deuterium to measure the electron neutrino content at the same time. The nuclear
reactor source of neutrinos only makes electron type antineutrinos. These are of too low an energy to have charged current interactions if they transform into muon or tau neutrinos. But the transformed neutrinos would still have neutral current interactions. So the neutral current observations measured the total neutrino content and the charged current interactions measured only the electron type neutrinos. If the two measurements did not agree some of the electron neutrinos had been transformed. This in fact, was the method used by the Sudbury Neutrino Observatory (SNO) to resolve the solar neutrino puzzle. (The SNO group used the charged current neutrino reaction on deuterium $\nu_e D \rightarrow e^- pp$ to measure the electron neutrino content of the solar flux. They used the neutral current reaction $\nu D \rightarrow \nu pn$ to measure the flux of all types of neutrinos independently of the neutrino type.) Careful checks ultimately indicated that the conclusions of Pasierb et al.\cite{8} that neutrinos had transformed were in error.

The period of the 1970’s had many exciting neutrino observations which inspired subsequent work. Many of these including the high $y$ anomaly, $\mu \rightarrow e\gamma$, the Lubimov neutrino mass and the Pasierb neutrino oscillations turned out not to hold up. Others, such as the weak neutral current, survived an ambiguous origin to become cornerstones of modern particle physics.

Solar Neutrinos

While it is often assumed that the solar neutrino problem provided strong motivation to study neutrino oscillations I think this is not true. There were three possible explanations for the solar neutrino problem, and until the discovery of the Mikheyev-Smirnov\cite{9} effect in 1985, neutrino oscillations was the least popular. Both the nuclear chemistry method used for the initial observations and the obscure branch of the solar reaction model needed to produce the energetic neutrinos needed for that detection method were also suspect. The Mikheyev-Smirnov\cite{9} effect, also known as MSW, permitted large neutrino flavor changes from small neutrino mixing due to contributions of the neutrino electron charged current to the forward scattering amplitude. When traversing matter electron type neutrinos had an additional interaction with the electrons in the matter. This interaction, under certain conditions, can enhance neutrino oscillations. The MSW effect became better known in the west due to the work of Bethe\cite{10} in 1986.
Neutrino oscillations and the number of neutrino types

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A brief treatment of neutrino oscillations, generalized to an arbitrary number of neutrino types, is given as the basis for design of a feasible experiment to search for neutrino oscillations using the neutrino beam produced at a high-energy proton accelerator.

Inspiration

A number of incidents were instrumental in focusing attention on the neutrino oscillations question. The discovery of the $\tau$ lepton clearly indicated our knowledge of the lepton sector was incomplete. Thinking at the time was that such a charged lepton should be accompanied by a neutral massless partner, the $\nu_{\tau}$. The $\tau$ lepton was the first clear evidence for a third family.

The presence of three distinct neutrino types significantly expanded the phenomenology of neutrino oscillations. In particular the number of parameters to describe neutrino oscillations would rise to 4 angles, from the one needed when only two families were present. The work of Kobayashi and Maskawa had also made it clear that there was now enough structure in the lepton sector to permit the presence of CP violation, a very rare phenomenon at the time. (CP violation is a manifest difference in the properties of matter and antimatter. Kobayashi and Maskawa had pointed out that a physical theory needed three particle families, if it was to have enough degrees of freedom for the phenomena of CP violation to manifest itself. They built upon the work of Cabibbo who pointed out that nuclear beta decay via the weak charged current could be understood as a transition involving a superposition of the $d$ quark, normally found in protons and neutrons, with the much rarer strange quark.) The Mann and Primakoff paper stimulated a good deal of research. For example, considerations of the effect of bulk matter on neutrino transport were contemplated in response to the suggestion in that one would want 1,000 kilometer long neutrino beams slicing through a cord of the Earth. A number of existing neutrino exper-
ments were modified to make them more accessible to observing neutrino oscillations. Figure 1 shows the title and abstract from this paper[13].

Another issue in this period that contributed to the interest in neutrino oscillations was the general maturation of accelerator based neutrino physics. What had been an exotic and difficult program to create tertiary neutrino beams had come to fruition at most of the major high energy physics labs. The presence of such facilities made it much easier to take the next step in the study of neutrino properties. The interferometry method embodied in neutrino oscillations gave one high energy accelerator based access to neutrino mass scales of the order of electron volts. Neutrino oscillations are essentially an interferometric effect. (Multiple amplitudes lead to the same state and the amplitudes can interfere). The initial neutrino flavor state is a particular superposition of the neutrino mass states. Since the different neutrino mass states evolve in time at different rates an initially pure flavor state will turn into a superposition of flavor states at a future time. Measuring the flavor content as a function of time gives one access to both the degree of neutrino mixing, via the magnitude of the impurity, and the neutrino mass differences scale, by when the flavor variation emerges and reaches a maximum in time.

**Inspiration 2**

A second source of inspiration came from the very rapid progress in theoretical physics in the early 1970’s. Nonabellian gauge theories as part of the standard model started to appear to play a role in nature. The discovery of weak neutral currents provided experimental support for electro-weak unification, in the context of a gauge theory. Asymptotic freedom[17], the weakening of the strong interactions at high energy, the dynamics underlying quantum chromodynamics (QCD) was discovered. With the running of the strong interaction coupling constant came the possibility that at some momentum it would meet the electro-weak value and Grand Unified theories[18] (GUTS) were created. These theories combined three forces of nature into one large group and demonstrated how the underlying distinctions would emerge at normal energies. At some high energy, called the unification scale, all the interactions would be identical, with the same interaction strength. At lower energies the coupling constants and selection rules would diverge to form, what appear to be three distinct forces of nature.

Such unification was not without cost. Rather quickly it was realized that
some of the additional interactions present in Grand Unified theories would lead to new, rare phenomena\[19\], such as the decay of the proton to leptons and mesons. The final state of proton decay would conserve electric charge, angular momentum or spin and energy but it would not conserve the values of baryon number or lepton number. The theory was not in conflict with observation since the lifetime predicted was still several orders of magnitude longer than experimental limits on proton decay at the time.

The possibility of experimental confirmation of Grand Unified theories via the observation of proton decay became a goal of late 1970’s to early 1990’s particle physics and is still important today. No convincing evidence has been reported for proton instability. Even now, the best we have are upper limits on its lifetime. The story of how technical problems were solved to reduce costs such that massive detectors capable of making interesting measurements of the proton lifetime is a long one that we can not discuss here. A recent talk\[20\] outlines how the major design decisions were made in the period 1978-1979 and the first detectors constructed by 1982.

Much of the work described in the current paper took place in the context of a collaboration centered at the University of California at Irvine, the University of Michigan and Brookhaven National Laboratory, known as IMB. The collaboration was formed in early 1979 to construct a massive deep underground detector (eventually built near Cleveland, Ohio) to discover proton decay. The Irvine group included many of the co-discoverers of atmospheric neutrinos.

Figure 2 is a sketch of the detector used for this research. Reference \[21\] describes the search for proton decay and includes photographs and other illustrations of the methods employed.

Most early Grand Unified theories predicted that the proton would decay to a final state consisting of a positron and a neutral pion. The neutral pion would immediately decay to two photons giving a fairly clear signal. Some variations of the theories, including those incorporating supersymmetry predicted suppression of this decay mode but favored a decay mode containing a charged muon and a neutral K meson. The neutral K meson would also decay yielding a somewhat different signature. Some ability to distinguish the proton decay modes was an essential part of the experiments.

An experiment searching for rare processes such as proton decay must be very sensitive. A sensitive detector is subject to a very large number of detections of non-signal. Such non-signal is termed “background”. A proton decay detector needs to be very large to be sensitive to the signal
Figure 2: A sketch of the IMB detector which was used for much of the work described in this paper. The sketch shows the size of the cavity excavated out of salt and filled with ultrapure water. The lines and black dots represent the phototubes and cables used to read out light signals from Cherenkov light produced in the water by fast charged particles. The fiducial volume two meters in from the phototube planes is indicated by the internal rectangular solid. The fiducial mass is a bit over 3.3 kilotons.
but it must be well shielded to reduce the background to a level where it does not obscure the signal. All such low background experiments have been located underground since cosmic rays produce a substantial contribution to the background at the surface. Even underground the cosmic ray rate is at best reduced but never eliminated. This is because the high energy muon component of the surface cosmic rays interact primarily electromagnetically and so they lose energy fairly slowly in traversing matter. As a rule, the deeper the detector the fewer cosmic ray muons one must register and reject. One important trade-off is that excavation costs are higher the deeper one goes. So on a fixed budget one would have to construct a smaller detector at larger depths. In most cases the location of the underground laboratory has been determined by previously existing infrastructure such as a mine or mountain tunnel.

One form of non-signal, background, which is not attenuated by depth are interactions from the neutrinos produced by cosmic ray interactions in the atmosphere. A very efficient method for producing neutrinos in the atmosphere is by strong interaction production of pions. The pions decay readily to a muon and a muon neutrino. Many of the muons also decay before they reach the ground to yield an electron and two additional neutrinos (one each of electron and muon type). Neutrinos are very penetrating since they only interact via the weak interaction, so they are essentially unattenuated by any amount of terrestrial shielding.

The flux of these neutrinos can be calculated and an event rate estimated. The experimental challenge was to identify neutrino interactions so that they could not be confused with the proton decay signature. In principle it would be easy to distinguish the two. Protons decayed essentially at rest in the detector, with negligible momentum whereas entering neutrinos bring momentum, creating events with approximately equal energy and momentum. So one can distinguish the two classes of events by reconstructing the events and measuring their momentum.

Formulation I – Accelerator Experiments

The search for neutrino oscillations was begun most expeditiously by adapting existing facilities to the project. Once existing data had been checked, and no evidence for oscillations found, the next step was to try to extend the range of the searches. One project, experiment 704 (figure 3) at Brookhaven,
Figure 3: An event from the Brookhaven neutrino oscillations search. The detector design was typical of the time. It was composed of a large segmented volume of liquid scintillator. The segmentation permitted the crude reconstruction of the tracks in the event. In the sample event illustrated three scintillation cells have energy deposited in them. The recoil energy and direction, as well as a knowledge of the neutrino beam direction, permitted a reconstruction of the neutrino interaction.
utilized a neutrino detector that had been used to establish the properties of the weak neutral current\[22\]. To extend its sensitivity to neutrino oscillations the energy of the beam was lowered. Lowering the neutrino beam energy had several advantages. It extended the sensitivity to lower neutrino mass differences ($\Delta m^2$). At the lower energies the muon neutrinos in the beam would not interact because they had insufficient center of mass energy to produce a muon via the charged current interaction. Interactions could only occur if the muon neutrinos transformed into electron neutrinos. Lowering the production energy also had the advantage that no electron neutrinos were produced in the target since the beam was below kaon production threshold. Kaons are the major source of the electron neutrino content of accelerator based neutrino beams.

The experiment failed to find evidence for neutrino oscillations but gave the experimenters, many of whom went on to work on IMB, substantial experience with the neutrino oscillations problem. Among the lessons learned was a need for a good understanding of the neutrino flux and a very good understanding of the detector response to a potential oscillations signal. Figure 4 shows many of the participants in this early oscillations experiment.

**Formulation II – Neutrinos in Nature**

While the flux of atmospheric neutrinos was an annoyance to the search for proton decay, it was realized that such a signal also provided an opportunity to extended the study of neutrino oscillations to kinematic regions of mass differences, $\Delta m^2$ well below what would be feasible at accelerators or reactors. But to be effective the detector would have to be able to distinguish between different kinds of neutrino interactions. Fortunately the need to identify the proton decay final state to distinguish different models had similar requirements. The IMB detector\[23\] was designed with a high resolution time scale to facilitate reconstruction by time of flight and a coarse time resolution which extended out to 10 microseconds following an event to search for a delayed signal coming from a final state muon, $\mu \rightarrow e\nu\bar{\nu}$ (Figure 5). This coarse time scale, or second time scale was known as the “T2” scale and was to later give the name “T2 problem” to our discovery. The name came about since we failed to find sufficient event candidates within a delayed time window. These were measured with the T2 electronics. A potential problem with this part of the electronics would give a comparable result. Fortunately
Figure 4: Members of a dedicated neutrino oscillations experiment at Brookhaven National Laboratory in 1977. LoSecco is on the left and Larry Sulak is kneeling on the right. Bill Wang is kneeling to the right of LoSecco. Andy Soukas is in the middle of the group of accelerator operators standing in the back.
there were experimental ways to confirm the correct operation of the electronics, by measuring stopping muons penetrating from the surface. So we could rule out an instrumentation problem to explain the observations. But the name stuck. While massive shielded underground detectors were motivated, and funded initially to experimentally observe predictions of Grand Unified theories, it is noteworthy that even the earliest proposals\textsuperscript{23} clearly indicated that such detectors would also be able to explore “neutrino oscillations, matter effects and supernovae”. The groups active in the search for proton decay, for the most part, had substantial neutrino experience since the problems were similar in many ways. Neutrino observation also required massive well shielded detectors.

While the IMB proposal\textsuperscript{23} had mentioned neutrino oscillations the details were not filled in until spring of 1980. As part of the graduate school requirements at Harvard University, students were expected to prepare a project on a topic related to their thesis research and to present it as an oral exam. Bruce Cortez, a student of Larry Sulak, chose atmospheric neutrino oscillations as his qualifying orals topic\textsuperscript{24}. His work was fairly complete. It included details of the neutrino flight distance as a function of direction. Upward going neutrinos travel about 13,000 km but those going down only travel about 15 km from their point of production in the atmosphere. The neutrino direction is determined from the direction of the momentum of the reconstructed neutrino interaction. Though, in principle one got all of the distances in between the transition from up to down distance scales occurs very rapidly over a fairly small part of the total solid angle near the horizon so, in essence one was dealing with an approximately 2 distance neutrino experiment. The correlation of neutrino direction, with the direction reconstructed from the final states was studied. For most neutrino events the reconstructed direction of the outgoing muon or electron provides a reasonable estimate of the neutrino direction (and hence path length) but this concordance tends to be less reliable at lower energies. Fortunately the problem does not prevent telling up from down. The work showed that for about two orders of magnitude $\Delta m^2$, from below $10^{-4} \text{eV}^2$ to about $10^{-2} \text{eV}^2$ one would have a very clear difference in the electron to muon ratio measured for upward events compared to the observed value for downward events. The downward events provided a short range sample to which the long range upward going events could be compared. Figures prepared for this work also showed a substantial distortion in the neutrino spectra if $\Delta m^2$ were in a range just below or just above the one where the effect would be maximal. The Cortez oral work was
Figure 5: The block diagram for the IMB experiment electronics. This provided an effective, accurate way to identify interactions leaving a muon in the detector. The design utilizes the approximately 2 microsecond lifetime of the muon to identify it. The electronics contained two time digitizers. The top one, labeled “Fine TAC” had a resolution of about a nanosecond and produces a measurement that is used to reconstruct the position and direction of the event. The center of the figure includes the design for a coarse time scale (labeled “Coarse TAC”), called a T2. This provided a 10 microsecond window, following a triggering interaction to observe particle decays of the products of the interaction. The rest of the electronics on the diagram provided for energy integration, and the ability to trigger the detector. A muon was identified when several phototubes gave a delayed signal following a triggered interaction.
documented in a number of conference talks[25, 26]. Figures 6 and 7 are the title pages from some of these talks. Figures 8 and 9 summarize most of the information needed to study atmospheric neutrino oscillations including the neutrino flux and cross sections, the variable distances and resolution issues. Figure 10 emphasizes the primary observable would be a difference in the electron to muon neutrino interaction rate as a function of neutrino direction.

So the atmospheric neutrino sample collected in the detector would include neutrinos with both short and long travel distances. Comparison of these samples would provide evidence for neutrino oscillations. The short ones would provide a control sample of unmodified neutrinos that could be compared with the longer flight ones which could have oscillated over the extra flight time.

Preparation

Detector construction took up much of the period of 1980-1981. A first attempt to fill the detector was made in December 1981. Some flaws in design were discovered at that time but even the partial fill yielded important data on the detector performance. A memo[27] (figure 11) from early 1982 demonstrated the detector response to stopping comic ray muons even though only 1/3 of the detector had been filled. The particle identification system,
Figure 7: The title page for Sulak’s talk about the potential to observe the oscillations of atmospheric neutrinos presented at the 1980 First Workshop on Grand Unification (FWOGU) in New Hampshire.
Figure 8: Figures taken from the FWOGU and Erice talks illustrating the method to observe atmospheric neutrino oscillations with a detector that was already under construction to observe proton decay. The neutrino propagation distances and the neutrino energy spectrum are shown here.
Figure 9: Figures taken from the PWOGU and Erice talks illustrating the method to observe atmospheric neutrino oscillations. The neutrino energy and direction resolution are considered here.

Figure 19

Figure 20

We should also consider the effect on various neutrino oscillations induced by the different forward and backward scattering amplitudes in the matter. The resonant values of the neutrino energy and charge-current interactions, where \( v_{\mu} \) and \( v_{\tau} \) are mixed, are also shown. This effect can be understood by considering a more general range of oscillations than those explored in the present paper.
Figure 10: The expected ratio of electron neutrino interactions to muon neutrino interactions for those neutrinos going upward and those going downward plotted as a function of the (positive) neutrino mass difference. The difference between these two samples is sensitive to neutrino oscillations over a substantial range of mass differences.
the “T2” scale was validated. Muons from the surface stopped in the partially filled detector gave the expected delayed signal about 2 microseconds after they had stopped. Timing and energy distributions met expectations. The muons triggered the detector when they entered it. The subsequent muon decay populated the delayed time scale electronics. A substantial effort was made during the initial start-up period to understand the detector. One had to demonstrate that the device saw what was expected to be there, atmospheric neutrinos and cosmic ray muons, before one could believe that it was also capable of observing proton decay.

Since the atmospheric neutrinos were expected to be the only serious background to proton decay several efforts were made to control systematic errors associated with them. The atmospheric neutrino response in the detector was modeled using real neutrino interactions. We had access to the large sample of accelerator neutrino interactions acquired at CERN in the heavy liquid bubble chamber “Gargamelle”. These interactions were primarily on bromine, a slightly heavier nucleus than the oxygen found in our water. But we needed a sample of neutrino interactions on nuclei since these would include absorption, rescattering and Fermi motion effects caused by the other nucleons in the nucleus. Subsequent to the work with the “Gargamelle” events we also studied events on neon from Brookhaven and on deuterium from Argonne. Several neutrino interaction models were also prepared to facilitate comparison and gauge systematic error.

The experiment was fortunate in that it had access to a large convenient sample of stopping muons to calibrate the detector response to muon decay. In a memo of summer 1983 [28] (figure [12]) Bill Foster described the way in which “Gargamelle” events were converted to IMB events and were simulated to understand the background. That note has a very interesting concluding paragraph.

“It has come to my attention that the electron angular distribution from $\mu \rightarrow e\nu\nu$ decay are backwards (for muons from neutrinos) on this tape. This may have an effect on the fraction of observable $\mu \rightarrow e$ decays, which Bruce says is somewhat higher than the data. This may be corrected in a future release when I get back from Paris.”

The simulation had more muon decay events than had been observed in the detector. This became know as the T2 problem. Something needed to be understood. The search was on to find some systematic error that could account for the discrepancy. As the quote indicates, the muon polarization was considered a possible candidate for the cause. The physical significance
Figure 11: Heading from a 1982 internal report on calibrating the detector response to muon decays. This work was done well before the detector was completed.
Figure 12: Portions of Bill Foster’s memo of July 1983, which describes the way in which neutrino interactions were simulated in the detector. At the end of this memo he notes a discrepancy between the observed number of muon decays and the number expected based on this simulation.
of this remark is that the spin direction of muons coming from neutrino interactions is opposite that of muons coming from pion decay. The calibration response based on stopped muon decays could be slightly different than the detector response to muons formed by neutrino interactions.

**Observation**

The September 1983 Harvard PhD. theses of Bruce Cortez and Bill Foster[29] contained the first physics to emerge from the class of experiments initiated to discover proton decay. Their data sample consisted of 112 contained events collected over a period of 130 days. They had searched for proton decay into the decay modes, lepton $K^0$ and $e^+\pi^0$. No evidence for proton decay had been found. The data sample included 25 events which had a muon decay. This was $22\pm4\%$ of the sample when $33\%$ had been expected.

This muon deficit, which was 2.5 standard deviations too low, was the net result of the discrepancy mentioned at the end of the previous section.

Followup of this “T2 problem” came with work by Eric Shumard, summarized in his 1984 PhD. thesis[30] for the University of Michigan. A major portion of Shumard’s thesis was devoted to extensive study of the IMB detector’s response to muon decay. He did a very careful job of measuring and modeling the muon identification process. He included all effects such as muon polarization, absorption, reflections of light and after-pulsing of phototubes. The thesis was based on 148 contained events collected over 202 days. The sample included 39 events with muon decays, which was $26.4\pm3.6\%$ but $35\%$ of the sample, 52 events, were expected. Shumard had succeeded in improving the responsiveness of the detector to muon decays, and hence the ability to recognize muon neutrino interactions. But in spite of this effort the observations were still about 2.4 standard deviations below expectations.

As was typical at the time, the topic of Shumard’s PhD. thesis was proton decay. He also reported no evidence for this process.

The IMB-1 detector ran for 417 days of live time before undergoing modifications to what eventually became IMB-3. The raw data from IMB was analyzed twice, by two independent programs to increase the detection efficiency and to guard against potential systematic bias. One of these streams was based at Caltech and Irvine and was known as the “West coast” analysis. The October, 1985 Caltech PhD. thesis of Geoff Blewitt[31] included 326 contained events, from only the “West coast” version of the reconstruction
streams. He reported a muon decay rate that was 2.8 standard deviations too low.

The full IMB-1 data sample consisted of a merger of both analyses. It had 401 contained events. Of these 104 had a muon decay. This $26\pm2\%$ observed muon decay rate was 3.5 standard deviations below the expected rate of $34\pm1\%$.

The evidence for an atmospheric muon neutrino deficit emerged gradually as data accumulated and consistency checks were made. At the IMB depth there was a reasonable source of stopping surface muons that provided a valuable resource to ensure we understood the detector response. Statistical errors drop with time as more data is accumulated but experiments can be limited by systematic effects which, in general, are not improved by more data. Systematic effects can be controlled by comparison with a known signal, such as the pure sample of muons from pion decay in the atmosphere that penetrate the Earth and stop in the detector. Small details in experimental design, such as the delayed time coincidence of the IMB electronics can make a big difference in the control of these systematic effects.

In February of 1986 I was invited to give a talk at the Lake Louise meeting (a series of winter institutes held in the Canadian Rockies) summarizing the status of the search for proton decay. As part of the talk I reviewed the atmospheric neutrino observations (figure 13). I mentioned the IMB muon discrepancy of 26%. “If 40% of the $\nu_\mu$ interactions do not result in a muon decay signal the observed value corresponds to $\nu_e/\nu_\mu$ of 1.3”. The expected value for such a ratio was 0.64. Two other experiments had values for this observable which I reported. The Nusex experiment, an iron calorimeter in the Mont Blanc tunnel had reported a value of $0.28\pm0.11$. The Kamioka experiment, using a novel method to distinguish showering from nonshowering events in water detectors had reported a value of $0.36\pm0.08$. I had no explanation for the apparent discrepancy between the IMB observations and the two other experiments.

As part of the effort to understand the background to proton decay there were extensive efforts to understand the details of neutrino interactions and their final states. The use of actual bubble chamber neutrino interactions in early simulations was a way to avoid confronting the problem but detailed models were produced and compared with observations. One of the first to construct a model and compare it with the data was Todd Haines of Irvine. The agreement was quite good, except for the observed rate of muon decays. This work on modeling the neutrino background was
Most proton decay detectors have reported a neutrino flux as measured in their detectors\(^4,5,8,12\). In general the agreement with expected fluxes is good. Both the Kamioka detector\(^1\) and the Nusex detector\(^4\) can distinguish \(\nu_e\) from \(\nu_\mu\) by shower development. They quote a \(\nu_e/\nu_\mu\) flux ratio of 0.36 ± 0.08 and 0.28 ± 0.11 respectively. These are lower than the expected value\(^6\) of 0.64. The IMB group has studied the fraction of their contained events resulting in a muon decay\(^8\). The 26% observed can be converted to a \(\nu_e/\nu_\mu\) ratio with a number of assumptions about muon capture in water. If 40% of the \(\nu_\mu\) interactions do not result in a muon decay signal the observed value corresponds to \(\nu_e/\nu_\mu \approx 1.3\).

The problem of the \(\nu_e/\nu_\mu\) ratio is still under active study. There is no directional dependence of the muon rate.

Figure 13: A portion of the proceedings of the 1986 Lake Louise meeting in which I point out a discrepancy between the IMB muon observations and expectations and the reports of two other experiments.

Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svooba, J. C. van der Velde, and C. Wuest

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Figure 14: The title and author list from the IMB journal article which noted the atmospheric neutrino anomaly.
published in 1986 (figure 14). The paper noted the muon rate discrepancy. The title of the paper “Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search” was appropriate for a paper comparing observations with estimates. The paper did not provide an explanation (figure 15). “This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon $\nu^\mu$’s to electron $\nu^e$’s in the atmospheric fluxes, (ii) an incorrect estimate of the efficiency for our observing a muon decay, or (iii) some other as-yet-unaccounted-for physics.” The diversity of interpretations reflected the diverse opinions of the authors. In reality, the first two possible hypotheses could at best reduce the statistical significance of the result. Any uncertainty in the flux or the muon decay rate could not correct for the apparent 40% reduction in the muon neutrino interaction rate the observations suggested. The large scale of the anomaly was reflected in my earlier Lake Louise quote above. After correcting for inefficiencies the muon neutrino data was almost a factor of 2 off from expectations.

It is noteworthy that most collaborations, including IMB can be very
conservative. As can be clearly seen in many documents leading up to this period, such as the PhD. theses quoted, most people hoped that the effect would just go away since it constituted an uncertainty to the background to proton decay. In fact the muon decay deficiency was not mentioned in early drafts of the 1986 article. It was added, at my insistence, since the topic of the paper, comparing neutrino observations with expectations, seemed appropriate.

While people have voiced criticism of the wording used in this paper, because of the multiple hypotheses provided. The multiple hypotheses was a compromise among the authors that permitted a significant effect to be reported to a larger audience. This journal publication alerted the scientific community to an important discrepancy of the muon neutrino rate when both Nusex and Kamiokande had reported no such problems.

The error reported on the observed muon decay rate in the published letter was ±3% rather than the ±2% mentioned earlier. The smaller value, calculated using binomial statistics is correct because binomial statistics ensures that the error on the fraction of events with a muon decay is exactly the same as the error on the fraction of events without a muon decay. The error can be easily calculated from the numbers in the paper.

**Interpretation**

Interpretation of the observations was difficult. Except for the deficiency of the muon decay rate, distributions did not look like those expected from neutrino oscillations as studied in the early 1980 work by Cortez and Sulak. Two component neutrino oscillations can be described by the equation

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\eta) \sin^2(1.27\Delta m^2 \frac{L}{E}) \]

Where \(\sin^2(2\eta)\) and \(\Delta m^2\) are constants of nature that determine the magnitude and time scale of the effect. A sign of neutrino oscillations is given by the \(\frac{L}{E}\) dependence, where \(L\) is the distance the neutrino has traveled and \(E\) is the neutrino energy.

There was no up down asymmetry which might be expected because of the different distances traveled by the downward and upward going neutrinos. There was no distortion of the energy spectrum. The event rate was as expected. 401 events had been observed when 402 were expected.
Figure 16: A group photo of the IMB collaboration in 1987. The photograph was taken at a meeting in Irvine in which the observation of neutrinos from supernova 1987a was celebrated.
Figure 17: Illustrations taken from the proceeding of the cosmic ray conference in San Diego in 1985. The upper part of the figure shows a neutrino oscillations exclusion region calculated based on the absence of spectral distortion in comparing the upward going to downward going neutrino events with a muon decay signature. The lower part of the figure compares the expected and observed E/L distribution for neutrino interaction in IMB-1. A problem in the -2.23 bin was noted in the text.
Figure 18: IMB-3 data similar to figure 17. This figure was shown at a cosmology meeting in the Baksan Valley of the Soviet Union in 1991. The lower distribution is similar to that of figure 17 but this figure includes only events with an identified muon. In figure 17 it included all single track contained events from the earlier IMB-1 data sample.
Comparison of the neutrino energy divided by neutrino flight path (E/L) showed only minor differences\[37\] between data and simulation (figure\[17\]). The article\[37\] did comment on the poor fit of the data to expectations in figure\[17\] by noting that most of the \(\chi^2\) came from the “E/L = 5.8 \times 10^{-3}\) MeV/meter.”

This absence of unusual distributions was also found in the IMB-3 data sample\[38\] (figure\[18\]) taken many years later. The IMB-3 sample was independent. The IMB-3 detector had four times the light collection of IMB-1 and utilized several pattern based particle identification methods to find muon neutrino interactions independently of the muon decay signal. The text of\[38\] also noted a poor fit for the bin corresponding to “\(\Delta m^2\) of 4\times10^{-3}\) eV^2”.

The normality of distributions was used to publish limits on neutrino decay\[39\], matter effects\[40\] and neutrino oscillations\[41\] in the range \(\Delta m^2 < 10^{-4}\) eV^2.
Figure 20: The atmospheric neutrino spectrum observed with Kamiokande I. The upper curve illustrates the good agreement for muon type events. The lower figure is for electron like events.

**Consternation**

One source of discomfort was that several other observations of atmospheric neutrinos reported no deficit of muon events. For example, the Kamioka equivalent of the IMB anomaly paper, submitted at about the same time emphasized the good agreement of observations with expectations (figure 19). “Note the comparison is absolute. i.e. no normalization has been made.” This publication summarized the Kamioka I data sample. It illustrated good agreement for both S, showering type events and for M, muon type events (figure 20). If anything, the data presented had a modest excess of M type events.

The Kamioka detector had much more light collection capability than the IMB detector. This permitted them to utilize the shape of the Cherenkov image to determine if the interaction had produced a muon, M type events, or an electron, S type events. The S stands for showering since the electron would multiple scatter, bremsstrahlung and pair produce; a processes known as an electromagnetic shower. Muon induced events had a much crisper,
Kamioka had used this difference in images to distinguish electron from muon type events.

While Nakahata et al. [42] had no numbers for data, the data was the same as the Kajita PhD. thesis [46] from earlier in 1986. The figures containing experimental observations are identical. Kajita’s PhD. thesis [46] reported the observations from the first phase of Kamioka, known as Kamiokande I. In an exposure of 1.11 kt-yr they reported 141 contained event in 474 days of live time. The ability to distinguish showering from non-showering tracks permitted them to report the event rates in the two categories.

(A kiloton-year is a measure of sensitivity to proton decay or atmospheric neutrinos. It means every nucleon in 1000 metric tons was observed for a year. One would expect twice as many interactions in two kiloton-years as in one kiloton-year. This could be accomplished by observing twice the mass or by observing the same one kiloton for two years. The neutrino flux does have some modest time variation, due to the effect of the sun’s cycle on the Earth’s magnetic field. Also atmospheric neutrino fluxes are not uniform. Again due to the Earth’s magnetic field there is some local variation of the flux from place to place on Earth. So a kiloton-year at one place will not yield the same neutrino interactions as at another location.)

Kamiokande reported 97 single prong events (89 with energies above 100 MeV) when they expected to observe 94 (85 with energies above 100 MeV). So the reported event rate was as expected. They reported 64 M type, or muon type, events when 54 were expected. They reported 33 S type events, electrons (25 above 100 MeV) when 40 were expected (31 above 100 MeV). The reason for mentioning the S type event rate above 100 MeV is that muon decay from sub threshold muons could look like showering low energy electron events. Cosmic ray sub threshold muons could slip into the device undetected and look like low energy electron neutrino interactions.

The Kamiokande I detector was capable of recording delayed muon decays associated with an event. 29 events had muon decays when 39.3 were expected.

These numbers are all in the thesis [46]. The thesis conclusions are that the muon and electron fractions are as expected. “These figures indicate that the agreement between the data and the simulation is quite well.” [46]

But the numbers quoted above clearly indicate a 2.4 standard deviation deficiency of muon decay signals and a 1.6 standard deviation excess of M type events, when compared to expectations. None of these significances is calculated in the thesis. I realized that the low muon decay rate reported,
but not noted by Kamiokande could provide confirmation of the IMB-1 3.5 standard deviation observation.

In June of 1986 I visited Tokyo following the neutrino meeting at Sendai and met with Koshiba and Kajita. I was well received. Koshiba took me and a small contingent of his group to a nearby noodle restaurant for a lesson in the art of slurping. The IMB anomaly paper had recently been submitted for publication. I discussed our observed muon decay deficiency. I pointed out the discrepancy between the M/S analysis and the muon decay rates in the Kamiokande analyses. The response was kind, blank stares. I was assured that the M/S analysis was correct.

Kajita’s thesis[46] and the Nakahata paper[42] were not unique. All Kamiokande reports stressed how closely the neutrino observations matched expectations (table 1).

Confirmation

In 1988 the Kamiokande experiment published a paper (Hirata et al.[47]) confirming the reported deficit of muon like neutrinos. The paper was based on an exposure to November 1987 with 277 contained events (265 above 100 MeV). It had 2.87 kiloton-years of data, including the 1.11 kiloton-years from Kamiokande I. The M/S (muon and showering) pattern recognition classification method had been modified to give agreement with the muon decay rate. The paper concluded that there appeared to be a muon deficiency. Only 59% of the expected number of muon type events were observed.

The Hirata et al. paper cites and quotes the 1986 IMB muon decay deficiency[36].

Interpretation of the data in this paper is still difficult since it also shows no directional modulation (figure 21) or energy distortion. A careful reading does indicate that the event rate appeared to be lower than that reported for the Kamiokande I data.

A brief review of the reports from Kamiokande from turn on to the 1988 paper shows a significant change in interpretation in the 1988 paper. Table 1 indicates that prior to 1988 the observed event rate was close to expectations, if a bit high, as was the rate of muon (or M) type events.

Table 1 also helps us resolve an issue as to the date of the Kajita PhD. thesis[46]. The report date was February 1986 as was the cover, but the title page lists February 1985. At the 6’th WGU in April 1985 Kamiokande
Figure 21: The angular distribution for electron neutrinos (left) and muon neutrinos (right) reported by Kamiokande in their 1988 paper confirming the atmospheric neutrino anomaly. Note that cosine of one is for downward going events. The original caption to this figure reads “Zenith angle distributions for; (a) electron-like events and (b) muon-like events. \( \cos(\theta) = 1 \) corresponds to downward going events. The histograms show the distributions expected from atmospheric neutrino interactions.”
| Source          | Date  | Exposure kt-yr | Events | M type Obs/MC | Event Rate per kt-yr | Expected Event Rate |
|-----------------|-------|---------------|--------|---------------|----------------------|---------------------|
| 5'th WGU [43]   | 1984  | 0.485         | 80     | Agreed        | 165                  | Agreed              |
| Arisaka Thesis [44] | 1985  | 0.661         | 84     | 1.03          | 127                  | 129                 |
| 6'th WGU [45]   | 1985  | 0.840         | 99     | 1.13          | 118                  | 111                 |
| Kajita Thesis [46] | 1986  | 1.11          | 133    | 1.19          | 120                  | 108                 |
| Hirata et al. [47] | 1988  | 2.87          | 265    | 0.59          | 92                   | 111                 |

Table 1: History of Kamiokande atmospheric neutrino observations

reported on 840 ton-years of exposure, up to January 23, 1985. There could not have been enough data available from the 880 ton fiducial mass to get to 1.11 kiloton-years exposure of the thesis anytime in February 1985. So presumably the report date of 1986 is correct.

Epilogue

The story so far has established and confirmed the observation that atmospheric neutrinos had an apparent deficiency of muon type neutrinos. But just as in the section Scientific Context the course of scientific discovery, is rarely straight, there are a number of subtleties associated with the measurements.

Personal notes written in the 1988-1989 period indicate serious concern about the event rates reported in the Hirata et al. [47] paper. Kamiokande 1 had reported an event rate of 116±10 events per kiloton-year but the new paper based on combining this data with subsequent data had an event rate of 92.3±5.7 per kiloton-year (figure 22).

One can understand that the M/S numbers changed from earlier reports because the M/S fitting method had been revised but why should the event rate drop? The 2.87 kiloton-year in the paper was the sum of the 1.11 kiloton-year from Kamiokande I and 1.76 kiloton-year from Kamiokande II. By subtraction this means that Kamiokande II had 136 events in 1.76 kiloton-years or an event rate of 77.3±6.8 events/ktonyr, a drop of 38% from Kamiokande 1.

After discussing the rate change with Kamioka investigators at conferences they suggested that I write to the collaboration. An email [48] was sent on April 18, 1989 and a written reply dated August 12, 1989 came by post.
Figure 22: Portion of handwritten notes on the event rate discrepancy between earlier Kamiokande reports and the 1988 paper confirming the neutrino anomaly.
Figure 23: Portion of the 1989 letter from the Kamiokande collaboration which argues that the rate difference is not significant. The 1988 paper combined data from two detectors known as Kamiokande I and Kamiokande II. Apparently the event rate per kiloton-year was expected to be lower in Kamiokande II.

The response\textsuperscript{[49]} (figure 23) indicated that a refit of Kamiokande I had an event rate of 116\(\pm\)9.4 events/ktonyr, in good agreement with my estimates. They also indicated that both Kamiokande I and Kamiokande II had rates in agreement with expectations.

It would have been nice to see the muon neutrino fraction independently for these two exposures, Kamiokande I and II. But the data has never been released in a format that would make that possible.

My notes indicate that a neutrino event rate check was done with the independent IMB data sample. IMB-1 had an event rate of 106\(\pm\)5 event per kiloton-year. In the first 1.53 kt-yr of exposure IMB-3 had a rate of 110\(\pm\)10 per kiloton-year, for energies above 140 MeV. It would appear that the neutrino flux was stable over the period in question.

\section*{Conclusions}

The author is neither a philosopher nor an historian so readers are encouraged to draw their own conclusions. Scientific research is a human endeavor carried out by people with conflicting standards. Scientists are often expected to draw solid conclusions from incomplete data, while maintaining an open mind. Perhaps the best remedy for this conflict is redundancy and honest corroboration. In contrast to many of the issues mentioned in the
introduction the atmospheric neutrino anomaly turned out to be true and is an important window on beyond the standard model physics. The full story of the discovery is more complex than can be covered in this already long article. For example, attempts to reconcile our measurement of a muon deficiency with results from Nusex and Kamioka, which did not, have been left out. Such well reasoned attempts do not move this story forward.

In scientific research the answers are not in the back of the book and Nature does not read Physical Review Letters.

Fred Reines, a colleague on much of the work discussed here, formulated a poem to illustrate the challenges of observational science and is known to have recited it in the context of this research.

Ode to Frustration

If at first you don’t succeed
What did you expect?
Progress would be slow indeed
With nothing to reject.

A false step here, another there
It means you’re really trying
Besides, the struggle up the stair
Itself is satisfying.

So labor with your charming quarks
Though endless multiplying
And weigh each lepton, one by one,
And look for baryons dying.

Dimuon pairs, imploding stars
All vie for a solution
With quarks behind their prison bars
Compounding the confusion.

Oh, Pauli, Fermi guide us
Banish our illusions
And elevate our hunches
To sensible conclusions.
It took many years and various kinds of measurements to understand the atmospheric and solar neutrino observations. Over the course of time our view of the significance of the results has changed. But the story is not over. The neutrino sector still has some discrepant observations that do not fit into the picture and many parameters needed to finish the picture itself, such as the overall mass scale, are just starting to be measured.

**Thanks**

This work would have been impossible without the contributions of many people. Larry Sulak, Fred Reines, Maurice Goldhaber and Jack Van der Velde provided the leadership for the IMB experiment, which was in many ways the first large scale experiment in astro-particle physics. Many creative and hardworking people have contributed. Most have been mentioned in the article but should also be recognized here. Students Bruce Cortez, Bill Foster, Eric Shumard, Geoff Blewitt and Todd Haines all played an important role. The next generation included Dave Casper, Steve Dye and Clark McGrew who helped confirm the result with the IMB-3 data and some new, independent particle classification methods. Richard Bionta was a master at calibration and designed and constructed the system that converted raw detector information into useful physical observations. Tegid W. Jones, Danka Keilczewska and John Learned have provided brilliant independent interpretations of the various observations. Many additional members of the IMB collaboration contributed to its success.

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