The Origins of the Discovery of Atmospheric Neutrino Oscillations

A Physics Memoir

In the early seventies, the advent of high-energy neutrino beams, the *raison d'etre* for the construction of Fermilab, and high intensity beams at Brookhaven and at CERN, brought with them the discoveries of weak neutral currents and the weak structure of the proton. Wrong sign dimuons also appeared, a hidden precursor of charm.

The two species of neutrino then known, electron and muon, were considered distinct, point-like probes. Larry Sulak learned about neutrino oscillations from Pontecorvo, who convincingly announced the possibility of oscillations between the two species, similar to the strangeness oscillations in the neutral kaon system. Concomitantly, oscillating neutrinos implied the quantum mechanical necessity of at least one of the two neutrinos having non-zero mass.

Experimenters stretched to find ways of testing the oscillation hypothesis, but the phase space possibilities were daunting: orders of magnitude in each of the natural observables: 1) in the square of the mass difference, and 2) in the mixing angle describing the 2x2 matrix linking the weak eigenstates (ν_e and ν_μ) with the mass eigenstates. No theoretical guidance suggested where to hunt in this wide-open phase space.

The advent of grand unification theories in the middle 70's brought a heightened burst of interest. Their two predictions, proton decay and neutrino oscillations, became dual goals for a massive new detector.

The IMB Experiment

In the summer of 1976, Larry Sulak led the neutrino signatures group at the first Dumand Summer Study. Working on a suggestion from Markov, they detailed the capabilities of reconstructing the energy and direction of atmospheric neutrinos by observing the Cherenkov rings. They used the timing and pulse height from a large volume array of phototubes operating at the single photoelectron level, spaced at the light attenuation length in clear water. Both the secondary muon and the hadronic shower (including the muons from it) were to be observed. S. Miyake, who had been present for the presentations at the end of the workshop, took the Cherenkov idea back to Tokyo. Although the subsequent work on Dumand moved slowly due to insufficient resources, an alternative application of this technology would soon appear.

In the early 1970s, Sulak had been using a large liquid scintillator calorimeter to observe for the first time weak neutral-current neutrino-proton elastic scattering at Brookhaven. Between 1976 and 1978, he, John LoSecco (his postdoctoral fellow) and Bruce Cortez and Bill Foster (his Ph. D. students), designed and built the first low-energy accelerator neutrino beam (150 MeV from the delta resonance). The sent it into the calorimeter to search [1] explicitly for the oscillations of muon neutrinos. Failing to reach sufficient sensitivity, they realized that a much more massive detector was required. This realization, and the emergence of GUT theories that predicted proton decay, seemed to them to be ideally suited to the a ring-imaging Cherenkov calorimeter.

The first tentative proposal continued using the Brookhaven neutrino beam, extrapolating it north several hundred kilometes. They wished to observe the low energy beam at a wallestonite mine Sulak had located and inspected in upper New York state. (A rock from that visit still sits as a gift to Rubbia when Sulak presented the idea to him.) A scaled up version of the Brookhaven detector in the mine would search for proton decay, and would search for neutrino oscillations during the short accelerator beam bursts. Nick Samios was not in the least impressed with "the superposition of two cockamamie proposals." Further, the large required volume of scintillating oil would be too expensive even if the lab would back the project.

During 1978 at Harvard, LoSecco, Cortez, and Foster developed a proposal for an economical ($4M), massive, ring-imaging water Cerenkov calorimeter that could precisely measure interactions of atmospheric electron and muon neutrinos and distinguish them from potential proton decay events. They simulated the characteristics of the events in the suggested detector to determine the required resolutions. In the high bay area of the former Cambridge Electron Accelerator, they designed and built prototype pressure-tolerant photomultiplier (PM) housings, tested them to 8 atmospheres on hemispherical EMI tubes using a Percy Bridgeman hydrostatic press, and strung them up to the ceiling to simulate deployment and repair. They demonstrated for the first time that single photoelectron signals could be used while preserving timing at the 2 ns level.

Sulak presented this proposal [2] (with Cortez and LoSecco in attendance) at a conference in Madison in December 1978. Similar talks followed at Michigan, MIT, at the DOE, and at conferences during 1979. The presentation at the International Conference on Neutrino Physics in Bergen [3] included photographs of prototypes of fast, pressure tolerant photomultipliers (PMs) and single photoelectron signals through a full electronics chain. Large dynamic range in timing, necessary to identify muons, and in pulse height were shown. The key idea was to use a surface array (whose cost scales better than with volume), with inexpensive small PMs, and black walls to avoid any confusion from reflections.

Maurice Goldhaber was taken by the ideas and joined (the only person from Brookhaven). Rubbia snubbed the idea (10kT was too small; he wanted a megaton volume detector, more like Dumand). Sulak and Goldhaber recruited Fred Reines, who brought extensive underground experience (though with scintillating oil) at the Morton Salt mine at Fairport Harbor, OH. Adding colleagues from Michigan, Sulak formed the IMB collaboration. With a design essentially the same as in the Madison paper, they proposed in the spring of 1979 to built the first massive (10 kT) underground detector with 2000 5" photomultiplier (PM) tubes, observing both the time and pulse height of Cherenkov light at the single photoelectron level from relativistic charged particles traveling through ultra-pure water.

In 1980 at the Erice conference in March and at the First Workshop on Grand Unification in April, Sulak demonstrated detailed calculations and Monte Carlo simulations [4] that he and Cortez had performed for a search for neutrino oscillations with the proposed underground water detector. Sulak presented the up/down asymmetry in the electron-to-muon ratio as a signature of neutrino oscillations for the first time (see Fig. 1). The technique would be sensitive to mass differences of hundredths of an eV^2 (the natural unit for oscillations of near massless particles). As part of the Ph. D. requirements at Harvard, Cortez made his oral defense in the spring of 1980 on neutrino oscillations in IMB. He discussed the up/down asymmetry in atmospheric neutrinos, showing the detailed calculations for the detector. Shelly Glashow served on the examining committee. He, Frank Pipkin and Cos Papaliolios served as Harvard thesis advisors for Cortez and Foster when both moved to the University of Michigan with Sulak. Rubbia, furious at having Harvard students on a competing experiment at Michigan, stormed around saying he would make sure that Cortez and Foster never got Harvard Ph.D.'s! (They did, with flying colors.)

At first, federal support was not forthcoming, primarily since the particle physics program focused on accelerators, but also because the competition had become fierce. To trump the IMB proposal, David Cline and Rubbia, with characteristic prescience, proposed HPW as a megaton detector (100 times the IMB size). The linear dimension of this detector was much larger than the attenuation length of light, requiring an expensive volume placement of PMs, rather than the surface array of IMB. It would obtain superior energy resolution by having reflective walls to catch all the photons, instead of the absorptive walls in the IMB ring-imaging detector, where reflections would have smeared out the characteristic rings.

Requested by Sulak, Glashow, Abdus Salam, Steven Weinberg argued on behalf of IMB to the University of Michigan, garnering a $1M loan as seed monie from Harold Shapiro, the new president, to get the project started, to prod the DOE to fund the project, and to woo Sulak from Harvard to Michigan. Eventually the DOE invested in both proposals, granting $2M to IMB.

The compromise for HPW required diminishing it to a 1 kT device, 1/10 the size of IMB. With David Winn and William Worstell as students, HPW was eventually realized, but no significant publication ever emerged. Multiple reflections of the light caused such confusion that timing was lost and event reconstruction intractable. Plus, the detector was too small.

In the meantime, IMB was built in two years. Innovations included deadtimeless electronics with large dynamic range in time, developed by Foster and produced by Sulak's electronics protege, Eric Hazen. This was critical to identifying muons by their decay signature (at the insistence of Sulak) and to discriminating between muon- and electron-neutrino interactions. Sulak and Richard Bionta, his new postdoctoral fellow, developed a LED calibration ball, isotropic to 1%. With assistance from James Strait, one of Sulak's former BNL Ph. D. students, a nitrogen laser and isotropic Ludox scattering ball were developed to calibrate time and pulse height. Dan Sinclair perfected the neutrally buoyant/neutrally torqued PM housings (first demonstrated at Harvard in '78), the prototype reverse osmosis system, and the installation of a six-story test tank in an elevator shaft at Michigan. Some 20 undergraduates there build all of the housings and electronics and tested all of the PMs.

At the Fairport Harbor underground site, Bill Kropp and Hank Sobel arranged civil excavation and water purification with >40 m attenuation length, the dimension from PM plane to PM plane of the near cubic detector. James Stone joined Sulak as a research scientist and designed an inexpensive water tank using a black polyethylene reservoir liner against the bare salt walls. Jack Vander Velde honed the Monte Carlo simulations on calibration data as water poured into the tank.

The detector started taking data as it was filled in the fall of 1981. It worked as expected. After fixing an initial leak, the initial engineering run was complete and serious data was being recorded in the summer of 1982.

Using his electron-neutrino experience from Gargamelle, Tegid Winn Jones (with help from P. V. Ramana Murthy and Vander Velde) invented the directionality technique to isolate a solar neutrino signal. After the IMB detector was operational, rates were measured, fast electronics to handle solar neutrino rates were developed, and a solar neutrino proposal drafted. Alas, an unanticipated background due to the shallow depth, de-excitation gamma rays -- produced by cosmic ray muon-induced spallation -- proved insurmountable and the solar neutrino search abandoned.

Cortez perfected his simulation code and Foster wrote the reconstruction algorithms. With help from Bionta, this became the IMB "east coast" analysis code. It converted circular light distributions into reconstructed particle tracks, distinguishing atmospheric neutrino events from nucleon decay events. Having moved to CalTech, LoSecco, along with Woijtek Gawjewski at UC Irvine, developed the "west coast" single-track fitter. The two independent reconstruction techniques provided complementary tools, the comparison of which yielded a measure of the systematic error. With Eric Shumard, a Ph.D. student of Vander Velde, Sulak developed an LSI 11 joystick event display. Rotatable color-coded pictures aided pattern recognition, displaying events both in time and in pulse height.

Within a year of turn-on, Cortez (who identified muons in his search for proton decay to muon and pion), Foster, and Sulak found only 2/3 as many atmospheric muon neutrinos as expected. The poor knowledge of the cosmic ray flux, however, limited the statistical significance, as did the uncertainty in how many muon decays from pions produced in oxygen were to be expected. A 2.5 sigma lack of muons is reported [5] in both Foster and Cortez's 1983 theses. Eric Shumard's 1984 PhD thesis showed that no systematic effects or experimental artifacts were responsible for the missing muons. Tini Veltman, a reader on the thesis committee, provided ample critique.

After the first year of operation, the original 5" EMI hemispherical PMs developed an unexpected failure mode. The reverse osmosis water was so pure that it leached sodium from the glass, weakening and cracking it. This occasioned an upgrade to IMB. To improve the discrimination between muon and electron neutrinos, the light-collecting power was almost quadrupled: Sulak invented wave-shifting light-collector plates for the PM's. These complemented new 8" PMs, which he had first challenged Mr. Hiruma, president of Hamamatsu, to make in 1978, when only EMI responded to the first “request for quotation.” John Learned provided the Poisson photoelectron tracing program to Hamamatsu to design the 8" PM for IMB; we understand that that code was later used to design the 20” PM for Kamiokande, and that the IMB code is still in use by Hamamatsu.

In 1985 LoSecco implemented a neutrino oscillation analysis similar to Sulak's early suggestion to search for the azimuthally asymmetry in the electron/muon ratio. LoSecco attempted to make a self-consistent measurement, independent of knowledge of the neutrino flux. But after this cut on the data, the statistics were insufficient.

In June of 1986 IMB submitted the first paper announcing an atmospheric muon neutrino anomaly, T.J. Haines, *et al.* [6]. The quoted 3-sigma deficit of atmospheric muon neutrinos is the most conservative evaluation of the data. The significance is 3.7-sigma when the calculation is done traditionally, with binomial statistics, as advocated then independently by D. Kielczewska and by LoSecco. This original result, which had persisted over four years, convinced IMB that a much larger detector with greater statistics was necessary for a definitive experiment, setting the stage for Super-Kamiokande.

The Kamiokande Experiment

Toshi Koshiba was also taken by the goal of searching for proton decay. Having heard Miyake's report from Dumand of inexpensive detection using the Cherenkov effect in water, he proposed to put vertical slabs of iron with layers of water between them in the long tunnels of the Kamioka mine. Watanabe records that when they heard of Sulak's proposal of a volume detector, they changed their proposal to be similar, but chose to keep their plans of observing only pulse height (and not use fast timing). They had the foresight of engaging Hamamatsu in going beyond the 8" tubes requested by IMB to the biggest PM possible.

In the summer of 1983, 4.5 years after the initiation of IMB, Koshiba inaugurated the second detector, Kamiokande. It had only a third the fiducial size of IMB and only half the number of pixels. Koshiba optimized this detector for the detection of solar neutrinos: the greater depth of the Kamioka mine attenuated the cosmic ray muons, thus avoiding the background from spallation gammas discovered earlier by IMB. Hamamatsu had scaled up the IMB PM design to 20", allowing a spectacular 20-fold increase in photocathode coverage over IMB. Koshiba claimed that these tubes and their coverage were so superior that timing would not be necessary.

The solar neutrino signal was elusive in Kamiokande. Vertex and angular resolution were poor. It became clear that timing was an absolute necessity in determining the direction of a particle track. Without timing information, reconstructing 10 MeV tracks and separating them from spallation and other background proved impossible.

Upon obtaining his Ph.D. on the first results from IMB, Cortez accepted a prestigious Milliken Fellowship at Cal Tech. He and Al Mann joined Kamiokande. Cortez took code fron the IMB analysis to Japan, as well as the electronics expertise needed to put fast timing on the PMs.

The detector was upgraded as Kamiokande II. Cortez and Mann added fast timing to the tubes, enhancing signal to noise and allowing reconstruction of the neutrino direction. Their water filtration was upgraded to the reverse osmosis method developed by Culligan and IMB, decreasing the background from uranium and radon. With diminished radioactivity, Koshiba, Y. Suzuki (his postdoctoral fellow), and Y. Totsuka (his assistant professor colleague) achieved sufficiently low threshold to sense neutrinos from the sun. In 1989 they proved that electron neutrinos come from the sun, but found that the solar flux was only half that expected.

In contrast with the deficit of muons in IMB [6], the numbers published by T. Kajita, Koshiba's student, in his Ph. D. thesis of February 1986 were in complete agreement with their flux expectations, *i. e.* Kamiokande had no hint of a muon neutrino anomaly. LoSecco visited the Kamiokande group in May 1986 to ferret out the discrepancy in the muon rates. Koshiba and Kajita met LoSecco's claim of missing neutrinos "with blank stares." A summary of the Kamioka results [7] submitted in August 1986 reconfirmed that the observed muons in Kamiokande at the time agreed with the predicted atmospheric fluxes. Undoubtedly the systematic errors on atmospheric neutrino detection and on the electron-muon separation were large and not fully understood. The observation of a lack of muons would await data from the new Kamiokande II detector

Both IMB and Kamiokande II observed the first neutrinos from the stellar gravitational collapse of Supernova 1987, which led to many limits on the properties of neutrinos.

In 1988 Kamioka confirmed [8], at the 3.5 sigma level, the 1986 IMB observation of a lack of atmospheric muon neutrinos.

Super-Kamiokande

Since the IMB and Kamiokande observations of atmospheric neutrino oscillations were each not statistically compelling, and since proton decay had not been seen, before his retirement Koshiba worked on convincing the Japanese scientific community to fund at great expense (~$100M) a new generation detector, Super-Kamiokande. Koshiba's vision combined a fiducial volume seven times more massive than IMB (to obtain the required statistics) with the same 40% photocathode coverage of Kamiokande to retain sensitivity to solar neutrinos.

In 1990, the decade-old polyethylene reservoir liner of IMB outlived its 10 year lifetime guarantee and could no longer be maintained. Hoping for support for the SSC from Japan as a *quid pro quo*, the DOE "encouraged" IMB to join Kamioka in their Super-Kamiokande endeavor, rather than approve a second generation detector in the US. To achieve its potential, Super-K needed an outer detector to veto muons and background from the rock (which is much worse than in the salt mine selected for IMB). However, the Japanese government would not fund this part of the detector. The opportunity for a merger appeared.

Sulak interceded with Totsuka, who had become the Super-K spokesman, to initiate a collaboration with IMB. This was not easy since the Japanese collaboration with Penn had been a rocky one. Sulak had to convince them that IMB collaborators would be reliable and contributory. The PM's, waveshifting plates, fast electronics, etc. would be redeployed as an active outer detector for Super-K. Sobel and Stone would be the co-spokesmen for the US side.

For the first time a massive underground experiment could veto background coming from the surrounding rock with a separate detector. The energy threshold for solar neutrinos would be substantially lower, and the cosmic ray background to the atmospheric neutrinos would be severely cut. In 1998, the combined former teams of Kamiokande and IMB, with independent analyses on the two sides of the Pacific led by Kajita in Japan and Ed Kearns at Boston University, established the existence of atmospheric muon neutrino oscillations with high statistics [9].

L. R. Sulak, January 2002

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Figure 1

Figure 8 from Erice 1980 [4]: Ratios of electron to muon neutrinos, both from the upper and the lower hemisphere.

References

1. "The Time Evolution of a Long-Lived Muon Neutrino Beam," L. R. Sulak, Proc. Rencontre de Moriond" (Tran Thanh Van, ed.) Flaine, France, 6-12 March 1977. (BNL Experiment 704)

Proc. Int'l Conf. Neutrino Phy., Elbrus, USSR, 18-24 June 1977, Nauka Pub, Moscow, Vol. 2, p.280, 1978 and "Results of a 150 MeV Muon Neutrino Oscillation Experiment at the BNL.AGS and Implications for Future Experiments," B. Cortez *et al.,* Neutrino Oscillation Workshop (N. Baggett, ed.) BNL Press 51380, 1981, p. 61. Also in Gauge Theories of Massive Neutrinos and Proton Decay (B. Kursunoglu and A. Perlmutter, ed.) Plenum, 1981, p. 271

2."Studies of a Detector to Test for Baryon Stability to a Lifetime of 10^{33} Years", L.R. Sulak, Proceedings of the Seminar on Proton Stability, Madison (D. Cline, ed.) December 8, 1978, p. A1;
Also appeared as Harvard University Particle Physics Preprints HUPDM 2 and HUPP 252.
First proposal for a massive underground ring-imaging water Cherenkov detector. Although this paper focuses on proton decay, the critical signal to understand is atmospheric muon- and electron-neutrino induced. The promise for neutrino oscillation searches in this detector appears in Fig. 16 and in the conclusion on page 12.

Also presented at Workshops on High Energy Physics, G. Fox ed., Cal Tech, 12-18 February 1979 and Workshop on Cosmic Ray Air Shower Detectors (T. Gaisser, ed.), Salt Lake City 15-18 May 1979.

3. "A Nucleon Decay Search: Design of a New Experiment Sensitive to a Lifetime of 10^{33} Years", B. Cortez *et al.*, Int'l Conf. on Neutrino Physics 1979 (A. Haadtuft and C. Jarlskog, ed.), Trykk: Astvedt Industrier A/S, Vol. 3 (1979), p. 121, presented by L. R. Sulak
Photos of the prototype PMs in pressure-tolerant housing, the prototype electronics with high dynamics range in time and pulse hight, and scope traces of single photoelectron response were shown.

4. "A Long Baseline Neutrino Oscillation Experiment Sensitive to Mass Differences of Hundredths of an Electron Volt", B. Cortez and L.R. Sulak, Unification of the Fundamental Particle Interactions (S. Ferrara, J. Ellis, and P. Van Nieuwenhuizen, eds.) Erice, March 17-24, 1980, Plenum Press, (1980), pp. 661-671.
First presentation, by Sulak, of the use of the atmospheric electron to muon ratio and the up/down asymmetry as oscillation signature appears on pages 667 to 670..

"The Irvine-Michigan-Brookhaven Nucleon Decay Facility: Status Report on a Proton Decay Experiment Sensitive to a Lifetime of 10^{33} Years", and a Long Baseline Neutrino Oscillation Experiment Sensitive to Mass Differences of Hundredths of an Electron Volt, L. Sulak, First Workshop on Grand Unification (Paul H. Frampton, Sheldon L. Glashow, Asim Yildez, eds.), April 10-12, Math. Sci. Press, University of New Hampshire, (1980), p. 163-188.
Details on the capabilities of IMB for a neutrino oscillation search appear on pages 178 to 188.

"Neutrino-oscillation Search with Cosmic-Ray Neutrinos," D. S. Ayers, et al. Phys. Rev. D, vol.29, No. 5, p. 902-910 (1984), submitted July 1983. *Many of the figures and much of the text in this paper were taken directly from the two, much earlier conference proceedings above.*

5. "An Experimental Limit on Proton Decay: $p \rightarrow e^+ + \pi^\circ$", G. W. Foster and "A Search for Nucleon Decay Into Lepton and K^0", B. Cortez. Both are Harvard University Ph.D. Theses submitted September 1983. *See page 157 of the first and page 167 of the second, where the observed number of atmospheric muon neutrino events is 2.5 sigma lower than anticipated in IMB.*

6. "Calculation of Atmospheric Neutrino Induced Backgrounds in a Nucleon Decay Search", T.J. Haines et al., Phys. Rev. Lett. 57, (1986), submitted 6 June 1986. *The top of page 1989, states "34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%." If the calculation is done more realistically with binomial statistics, the significance of the effect is 3.7 sigma, as advocated by D. Kielczewska, J. LoSecco, L. Sulak and others at the time.*

7. "Atmospheric Neutrino Background and Pion Nuclear Effect for Kamioka Nucleon Decay Experiment," M. Nakahata *et al.*, J. Phys. Soc. Jpn., vol. 55, 3786 (1986), received August 1986.

8. "Experimental Study of the Atmospheric Neutrino Flux," K. S. Hirata *et. al.*, Phys. Lett., B205 (1988) p.416, received March 1988.

9. “Evidence for Oscillation of Atmospheric Neutrinos”, Y. Fukuda *et al.*, Phys. Rev. Lett. 81 (1998) p. 1562-1567. *Although initial Super-K work cited the IMB muon deficit of [6], the Japanese side of the collaboration declined to cite those results in this paper.*