Annotated Chronological Bibliography of the

Observation of the Oscillation of Atmospheric Muon Neutrinos

Development in the US

In the summer of 1976, Sulak leads 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.

0. "Signatures of High Energy Neutrino Interactions and their Detection Via Cherenkov Light," L. R. Sulak *et al*., Proc. of the 1976 Dumand Summer Study (A. Roberts, ed.) Honolulu, 6-19 September 1976, p. 297

In late 1978 and early 1979, Sulak presents the first conceptual design of a massive (10 kTon) ring-imaging calorimeter sensitive to proton decay events and to 1 GeV atmospheric neutrino interactions at a seminar at the University of Michigan, to a conference in Madison, Wisconsin, to a meeting at Chicago, and with Dr. B. Hildebrand at the U.S. Department of Energy (March 5, 1979).

1. "Studies of a Detector to Test for Baryon Stability to a Lifetime of 10^{33} Years", L. R. Sulak, Proceedings of the Symposium on Proton Stability, Madison (D. Cline, ed.), 8 December 1978, p. A1 (copies of transparencies).

Cortez, LoSecco and Sulak hand out copies of the written proposal as Harvard University preprint HUEP 252. A similar presentation with written handouts is given by Sulak at the Ohara Meeting on Proton Stability, organized by D. Cline, on January 11, 1979. LRS's presentations at the above conferences included photographs of technical advances achieved in Harvard Cambridge Electron Accelerator lab, with scope traces of single and double photoelectron peaks from hemispherical PMs with 1/4 photoelectron (pe) thresholds, 3 ns timing at the single photoelectron level for the total electronic system, neutrally-buoyant and neutrally-torqued suspension structure with 15 m height, pressure-tolerant PMs and leak tight mechanical mounting, tested electronics both at the PM base and after data acquisition with one pulse height and two timing scales, and a conceptual layout of underground site Details of this work are recorded in 25 HUPDM Technical Notes (see separate list).

At conferences in the winter and spring of 1979, presentations of the simulations and prototype work for this detector are given by Sulak and his Harvard Ph. D. students, B. Cortez and W. Foster. He moves to the University of Michigan with a promise from the new president of a loan sufficient to start building the detector by the end of the 1979:

2. "Studies of a Detector to Test for Baryon Stability to a Lifetime of 10^{33} Years", E. Chason, M. Claudson, B. Cortez, W. Stornetta, L. Sulak and P. Timbie, Workshops on High Energy Physics, California Institute of Technology, (G. Fox, ed. of copies of presentations) 12-18 February 1979.

3. "A Test of Baryon Stability Sensitive to a Lifetime of 10^{33} Years", E. Chason, M. Claudson, B. Cortez, W. Stornetta, L. Sulak and P. Timbie, Proceedings of the Workshop on Cosmic Ray Air Shower Detectors (T. Gaissier, ed.), Salt Lake City, (15-18 May 1979).

"...such a detector could yield...a search for neutrino oscillations at the level of 10^{-2} eV neutrino mass difference. (p. 129)"

4. "A Nucleon Decay Search: Design of a New Experiment Sensitive to a Lifetime of 10^{33} Years", presented by L. Sulak for M. Goldhaber *et al*., Proceedings of the International Conference on Neutrino Physics, Neutrino 1979, Bergen, Norway, 18-22 June 1979, (A. Haatuft and C. Jarlskog, ed.), Trykk: Astvedt Industrier A/S, Vol. 2 (1979) p. 121.

"...the neutrino spectrum from atmospheric cosmic rays can be predicted...it may be possible to extract...any deviation from the predicted fluxes...due to neutrino oscillations...(p. 141)"

5. "Proton Decay Experiments," L. R. Sulak, Proceedings of Workshop on Weak Interactions and Related Topics, Blacksburg, VA , December 1979 (L. N. Chang and L. W. Mo, eds.) p. 318.

In May 1979 the resultant proposal to the US Department. of Energy by the newly formed IMB collaboration advocates both proton decay and neutrino oscillation searches as a balanced research program:

6. "Proposal for a Nucleon Decay Detector," Irvine/Michigan/Brookhaven, May 25, 1979, for consideration by the DOE review panel meeting, Washington, D.C., May 31, 1979.

"...neutrino oscillations...would alter the expected 2/1 ratio of the ν_e to ν_μ with a dependence on zenith angle and energy that is unique...(with) limits on neutrino rest mass differences at the 10^{-2} eV level...(p. 96)"

Much of the seminal work for the above presentations and the IMB Proposal is accomplished by Sulak and his students at Harvard during the summer and fall of 1978 and the first half of 1979. This work is documented in a series of Harvard University Proton Decay Technical Memos (HUPDM). The most noteworthy are the following:

7. HUPDM 3, 7, 9, 19, and 25. Obtaining and testing a photomultiplier tube (PM) that is pressure tolerant, sensitive to a single photoelectron, economical, reproducible, and has low noise and 1 ns timing. (Although Sulak approaches several manufacturers, including Mr. Hiruma, president of Hamamatsu TV Corp., only EMI can produce an acceptable PM at the time.)

HUPDM 4, 11 and 15 Experimentally verifying the yield of Cherenkov photoelectrons in water, and developing an event reconstruction algorithm.

HUPDM 9, 20, and 21. Proof of principle design of economical electronics that provide 1 ns timing at the single photoelectron level, have large time dynamic range to identify decay electrons from muons, and have a pulse height response with high dynamic range.

HUPDM 6, 8, 13, 14, 16, 18, and 24. Design and prototyping of corrosion-resistant PM mechanical supports, a reservoir liner, and a reverse osmosis water purification system.

HUPDM 10 and 22. Cost estimate for all of the above.

In 1980 Sulak details the proposed neutrino oscillation search alluded to in the proposal. The double ratio of up-coming to down-going neutrinos of both muon and electron neutrinos is advocated for the first time. He shows that IMB would have sensitivity to squared neutrino mass differences in the 10^{-4} to 10^{-2} eV^2 range and demonstrates the calculations at the following conferences:

8. "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 Yildiz, eds.), Math Sci. Press, (1980), p. 163.

9. "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.) Europhysic Study Conference, Erice, Italy, March 17-24, 1980, Plenum (1980), p. 661.

"A flux independent asymmetry in the up/down ratio of the two neutrino species is the primary signal (p. 661)...the massive detector underconstruction...may provide the most sensitive detector for oscillation searches ...and may yield a signal for ν_e,ν_μ oscillations...if the expected 0.5 ratio of ν_e/ν_μ is not observed. (p. 670)"

In 1981 the 3.3 kTon fiducial mass of the IMB-1 detector is turned on and meets all expectations. However, after the first year of operation the 5" EMI PMs begin to crack due to unanticipated leaching of sodium from the glass by the ultra pure reverse osmosis water. Preparing for an upgrade of the detector (to IMB-2, then IMB-3), Sulak contacts Mr.

Hiruma again and urges deveIoPMent of a PM with less stress in the glass and a bigger, 8", diameter. IMB electron tracing codes are provided to aid in the deveIoPMent of bigger PMs.

Sulak, with his Ph. D. student R. Claus, invents a wavelength-shifting plate that mates with the PM and almost doubles the light collection while preserving the good timing for the IMB upgrade:

10. "A Waveshifter Light Collectors for a Water Cherenkov Detector", R. Claus, *et al*., Nucl. Instr. and Methods A261 (1987), p.540.

The parallel track in Japan

Following on the suggestion of S. Miyake who had attended the 1976 Dumand workshop, M. Koshiba initiated a proposal using inexpensive detection of the Cherenkov light in water. Watanabe reports that Koshiba proposed to put vertical slabs of iron 2 m high with a 1.6 m layer of water between them in the long tunnels of the Kamioka mine. (See figure 1, p. 69 of the paper below.)

11. "Trying to Measure the Proton's Life Time," Y. Watanabe, Proc. of the Workshop on Unified Theories and Baryon Number in the Universe," O. Sawada and A. Sugamoto, KEK, Feb. 12-14, 1979.

> "…I came across a paper by L. Sulak,[14] who describes a very similar detector backed up with Monte Carlo simulation….the number of photomultipliers necessary can be as few as 3000…makes his proposal very practical." p. 62.

These proceedings were reprinted in January 2004 for the Fujihara Seminar "Neutrino Mass and Seesaw Mechanism" by Y. Totsuka (Chairman). Referring to the article above with the idea to fill tunnels with 2m x 1.6m iron slabs and water, the Foreward states:

> "Watanabe …presented Koshiba's original idea of a large water Cherenkov detector for the proton decay search. Probably this was the first published article that mentioned Koshiba's idea explicitly."

The Koshiba team adopted the proposal of a volume detector with a surface array of tubes, but chose to keep their plans of observing only pulse height (and not use fast timing).

In July of 1983 the now volume Kamiokande detector, with no iron but with a fiducial mass of 0.88 kTons, starts data taking under the direction of Koshiba. It is outfitted with enormous 20" diameter PMs that permit 40% photocathode coverage of the walls of the detector. This large size PM is critical to achieve the low energy sensitivity (4 times more photoelectrons/MeV than IMB) tailored for the search for a real-time solar neutrino signal. Since Kamkiokande I has no timing electronics on the PMs, the superior charge collection from the big tubes would eventually provide a method of distinguishing muons from electrons by the non-showering *vs*. showering character of the pattern of hit PMs. The innovative PMs are a product of a collaboration set up by Koshiba between members of Kamiokande and Hamamatsu TV Corp.:

12. "The Kamiokande Photomultiplier Tubes," H. Kume *et al*., Nucl. Inst. and Meth., 205, p. 299 (1983).

In 1984 Sulak and collaborators propose an optimized technique for the analysis of data in searching for neutrino oscillations:

13. "Neutrino Oscillation Search with Cosmic-Ray Neutrinos", D.S. Ayres, B. Cortez, T.K. Gaisser, A.K. Mann, R.E. Shrock, and L.R. Sulak, Phys. Rev., D29 (March 1984), p. 902.

In 1985, Sulak's postdoctoral fellow, J. LoSecco, attempts to extract a neutrino oscillation signal from the data but is hampered by uncertainty in the knowledge of the neutrino fluxes:

14. "Test of Neutrino Oscillations Using Atmospheric Neutrinos", J.M. LoSecco *et al*., Phys. Rev. Lett., Vol. 54 (1985), p. 2299.

In 1986, IMB publishes the first observation of a deficiency of atmospheric muon neutrinos:

15. "Calculation of Atmospheric Neutrino Induced Backgrounds in a Nucleon Decay Search", T.J. Haines *et al*., Phys. Rev. Lett. 57 (1986), p. 1986.

"...401 contained events were observed (p. 1986)...simulation predicts that 34±1% of the events should have an identified muon decay while our data has 26±3%. This discrepancy could be...some other as-yet-unaccounted-for physics (p. 1989)"

In June 1986 on a trip to the Int'l Conf. on Neutrino Physics and Astrophysics, Sendai, Japan, LoSecco compares analyses with Koshiba's recent Ph. D student, T. Kajita. Unlike the IMB muon neutrino deficiency, Kajita's thesis on Kamiokande shows no muon neutrino discrepancy:

16. University of Tokyo Ph. D. Thesis, T. Kajita, February, 1986.

In 1991, another of Sulak's Ph. D students, D. Casper, completes an initial analysis of data from IMB-3, the upgraded IMB detector with bigger 8" Hamamatsu PMs outfitted with waveshifters, which had been running since 1986. In the upgraded detector, muon neutrino events are identified not only by their decay signature, as originally done in IMB, but also by the nonshowering characteristic of muon neutrino-induced events. A muon deficit is seen in the new data, but the statistical significance is not compelling:

17. "Measurement of Atmospheric Neutrino Composition with IMB-3", D. Casper *et al*., Phys. Rev. Let., 66 (1991), p. 2561.

"...nonshowering events comprise 41±3±2% of the total. The fraction expected is 51±5%. (p.2561) The fraction of events with muon decay...exhibits a similar discrepancy. ...the magnitude of the deviation is not sufficient to require neutrino oscillations to explain our data. (p.2564)" See also Univ. of Michigan Ph. D. thesis, D. Casper, 1990.

In 1992, with updated input for the neutrino flux simulation and higher statistics, the IMB-3 confirmation of the deficit of muon neutrinos becomes statistically significant:

18. "Electron-Neutrino and Muon-Neutrino Content of the Atmospheric Flux'', R. Becker-Szendy, *et al.,* Phys. Rev., D46 (1992), p. 3720.

"33±2% of events are accompanied by ...muon decays, while 43±1% are expected." "...the fraction of nonshowering events is 0.36±0.02±0.02...0.51±0.01±0.05 is expected. (p. 3720)" "Neutrino oscillations are a possible, though not necessary, explanation.(p.3724)"

Kamiokande, continued

Meanwhile, in 1988, the Kamiokande detector confirms the deficiency of muon neutrinos seen in IMB:

19. "Experimental Study of the Atmospheric Neutrino Flux", K. S. Hirata *et al*.,Phys. Lett. 205B, 416 (1988)

"We have observed 277 fully contained events...the number of muon-like single-prong events is 59±7% of the predicted...(p.416)"

Subsequent analysis by another of Koshiba's Ph. D. students, M. Takita, refines the Kamiokande observation:

20. T. Kajita *et al*., Proc. of the 25th Int'l Conf. on High Energy Physics, Singapore, 1990, (K. K. Phau and Y. Yamaguchi, eds.) World Scientific, 1991, p. 685 and also University of Tokyo Ph. D. Thesis, M. Takita, ICRR Report No. 186-89-3 (1989).

In 1992, Kamiokande fits the muon deficiency to a two component neutrino oscillation hypothesis for the first time, showing the allowed region in terms of mixing angle and mass difference:

21. "Observation of a small atmospheric ν_μ/ν_e ratio in Kamiokande", K. S. Hirata, *et al*., Phys. Lett., B280 (1992), p. 146.

Super-Kamiokande: a Japan – US collaboration

Earlier, in 1983, a prescient Koshiba, and later in 1986, Y. Totsuka (the former Ph. D. student of Koshiba who would become spokesman for the SuperKamiokande Collaboration) argue the physics case for a follow-up to the Kamiokande and IMB detectors:

22. Proceedings of the Workshop on Grand Unified Theories and Cosmology, M. Koshiba, KEK, Japan, December 1983, p. 24.

23. "Super-Kamiokande", Proceedings of the Seventh Workshop on Grand Unification/ICOBAN '86 (J. Arafune, ed.), Y. Totsuka, Toyama, Japan, April 1986, p. 118. See also KEK Report 85-6, Y. Totsuka 1985 and "SuperKamiokande Proposal" (in Japanese), February 1986.

In 1990 Totsuka presents the SuperK proposal to the Japanese government.

24. "Super-Kamiokande", Y. Totsuka, International Symposium on Underground Physics Experiments, Science Council of Japan, April 1990, ICRR-Report-227-90-20 (December 1990).

In April 1991 Japan starts funding Super-K. Upon completion of the IMB experiment in late 1991, Sulak (now at Boston University) phones and emails Totsuka proposing a Kamioka/IMB Collaboration. IMB would implement the outer detector for Super-K, an essential component left unfunded by the Japanese. IMB would contribute their PMs, waveshifting plates, electronics, and independent software. Sulak sends a letter of intent to Totsuka, suggesting meetings between the two in Philadelphia and in Boston from April 29 to May 6, 1992. .In his reply of February 17, 1992, Totsuka agrees to the meetings and to idea of the collaboration:

25. Letter from Sulak to Totsuka, January 29, 1992.

> "I have been asked by the IMB Collaboration to explore the possibility...of combining resources to build the world's best detector."

26. Reply from Totsuka to Sulak, February 17, 1992.

> "We are in general quite positive to...collaborate with the IMB group..."

In April 1996 Super-K starts to take data. The initial observations of atmospheric neutrino oscillations by IMB and Kamiokande are verified by a subgroup led by Kajita and E. Kearns (a member of Sulak's research team at Boston University). The data is analyzed by M. Messier, Boston Ph. D. student (the first on Super-K) to complete and by Y. Hayato, a Ph. D. student at the Tokyo Institute of Technology. The effect, now over 10 standard deviations in significance, is published in 1998:

27. "Evidence for oscillation of atmospheric neutrinos", Y. Fukuda *et al*., Phys. Rev. Lett., 81 (1998), p. 1562.

28. "Study of the atmospheric neutrino flux in the multi-GeV energy range", Y. Fukuda *et al*., Phys. Lett. B436 (1998), p.33.

29. "Measurement of a Small Atmospheric ν_μ/ν_e", Y . Fukuda *et al*., Phys. Lett., B433 (1998), p. 9-18.