The History of the Atmospheric Neutrino Anomaly

John LoSecco

University of Notre Dame

November 10, 2017

Caveats

- I am not a historian
- I am not unbiased
- I was a participant
- Sources
  - Journal Articles
  - Conference Proceedings
  - Theses (PhD and others)
  - Internal reports and memos
  - Notes
  - Memory!
- Selection Effect

Outline

- Scientific Context
- Inspiration
- Formulation
- Preparation
- Observation
- Consternation
- Confirmation
- Epilogue

Scientific Context

- Primarily period 1978-1988
- Notable Observations
  - Alternating Neutral Currents
  - The High y Anomaly
  - $\mu \to e\gamma$ at SIN! (TRIUMF over SIN)
  - Lubimov $\bar{\nu}_e$ Mass
  - Pasierb *et al.* $\nu D \to \nu PN$ Reactor neutrino Oscillations

Positive Context

Many real discoveries from that period

- Renomalization of gauge theories
- Discovery of weak neutral currents
- Asymptotic Freedom
- J/Ψ charm bound state
- Grand unified theories invented
- τ lepton discovered
- Charm D mesons found
- Υ $B\bar{B}$ discovered
- W and Z mesons discovered

Inspiration I

- Discovery of the τ
- Mann and Primakoff ν Oscillations Paper 1976

PHYSICAL REVIEW D VOLUME 15, NUMBER 3 1 FEBRUARY 1977

Neutrino oscillations and the number of neutrino types*

A. K. Mann and H. Primakoff

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174

(Received 7 July 1976; revised manuscript received 27 September 1976)

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.

  - Extended the idea of ν oscillations to > 2 flavors
  - Inspired Renaissance in the subject
  - Inspired by the possibility of "right handed currents" from the high y anomaly!
  - Long baseline ideas in this paper also inspired studies of matter effects
  - Mentions CP violation
- Maturation of accelerator neutrino physics

Inspiration II

- Asymptotic Freedom
- Grand Unified Theories - SU(5)
- Baryon Instability
- Super-symmetric Grand Unification and $\mu^+ k^0$
- Very Large but feasible detectors
- Neutrino Induced Backgrounds to Proton Decay

Proton Decay

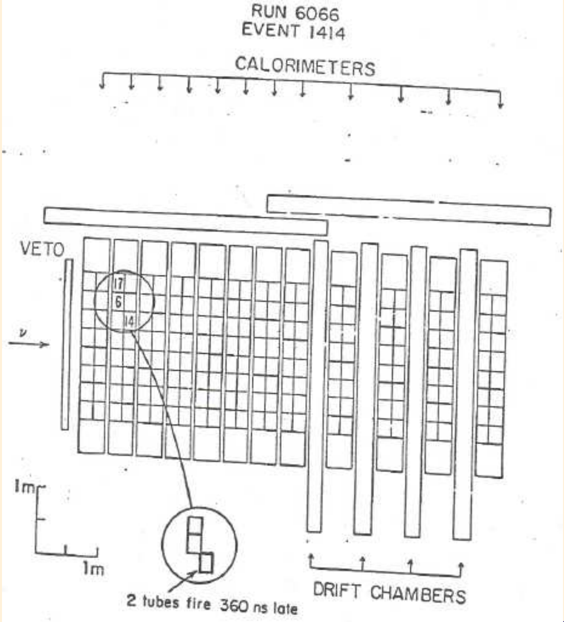
- Asymptotic freedom. Strong interactions get weak.
- Grand unified theories included strong, electromagnetic and weak interactions.
- At the Unification energy (10^{15} GeV) scale all forces have the same strength
- At lower energies the symmetry appears to be broken
- SU(5) $\rightarrow$ SU(3) $\times$ SU(2) $\times$ U(1)
- SU(5) has 24 interactions. SU(3) $\times$ SU(2) $\times$ U(1) have a total of 12 interactions
- The extra 12 interactions mediate the conversions of quarks into leptons.
- Protons can decay ($P \rightarrow e^+\pi^0$) mediated by bosons with a mass of the unification scale. ... slow 10^{30} years

Formulation I - Accelerator Experiments

- Brookhaven E704 - January 1977

- ▸ Low energy accelerator ν beam
- ▸ P_{Beam} 1.5 Gev/c
- ▸ Below K threshold. No K_{e3} decays
- ▸ L/E $\approx$ 1 m/MeV
- ▸ Most ν_μ below CC threshold

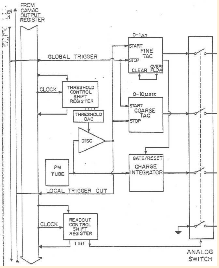
E704 Event



RUN 6066
EVENT 1414
CALORIMETERS
VETO
17
6
14
ν
1m
1m
2 tubes fire 360 ns late
DRIFT CHAMBERS

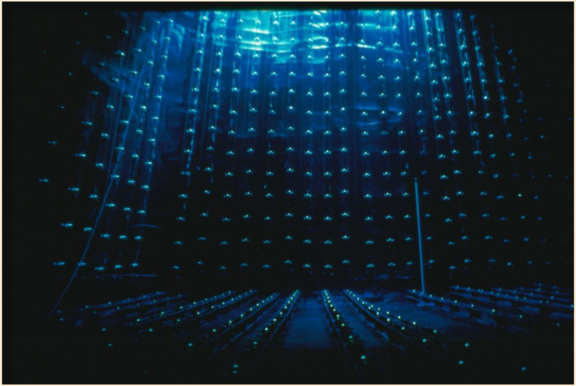
Formulation II - Non-Accelerator Experiments

- Neutrino Signal in Proton Decay Detectors
- Extend the Δm^2 range
- The “T2” scale and particle identification
- IMB proposal (1979) mentions neutrino oscillations, matter effects and supernovae as additional physics goals
- UCL (TWJ) joined and suggested *solar neutrinos*



IMB Detector

8000 tons of water – 5×10^{33} Nucleons
Imaging Cherenkov detector
Surface array
Tracking and energy from light timing and pulse height



New enabling technology ...

- Early 1980 Cortez Harvard Oral Exam
  - Details of ν path lengths
  - Direction resolution
  - ν_e/ν_μ for upper and lower hemispheres
  - Documented in Sulak Erice talk, March 1980, the second half of Sulak FWOGU talk and 1984 PhyReV

A LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT SENSITIVE TO MASS DIFFERENCES OF HUNDREDTHS OF AN ELECTRON VOLT[#]

B. Cortez[†] and L.R. Sulak[*]

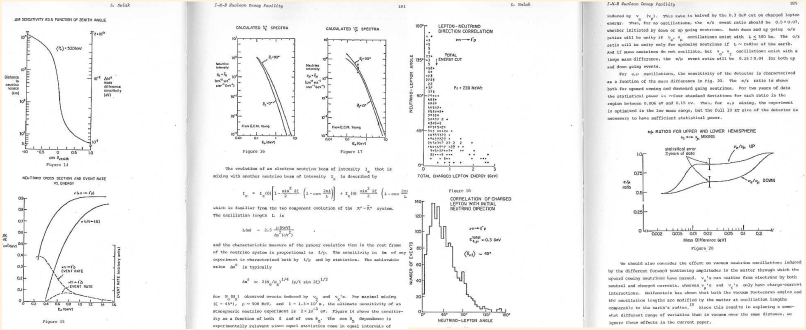
Harvard University
Cambridge, MA 02138

University of Michigan
Ann Arbor, MI 48109

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**

Randall Laboratory
University of Michigan
Ann Arbor, Michigan 48109



L. Sulak

ΔM SENSITIVITY AS A FUNCTION OF ZENITH ANGLE

Figure 14

NEUTRINO CROSS SECTION AND EVENT RATE VS. ENERGY

Figure 15

I-M-B Nucleon Decay Facility 181

CALCULATED $\overset{(-)}{\nu}_e$ SPECTRA

CALCULATED $\overset{(-)}{\nu}_\mu$ SPECTRA

Figure 16

Figure 17

The evolution of an electron neutrino beam of intensity I_e that is mixing with another neutrino beam of intensity I_x is described by

$$I_e = I_e(0)\left[1 - \frac{\sin^2 2\xi}{2}\left(1 - \cos\frac{2\pi\ell}{L}\right)\right] + I_x(0)\,\frac{\sin^2 2\xi}{2}\left(1 - \cos\frac{2\pi\ell}{L}\right)$$

which is familiar from the two component evolution of the $K^\circ - \bar{K}^\circ$ system. The oscillation length L is

$$L(m) = 2.5\,\frac{p(\mathrm{MeV})}{\Delta m^2(\mathrm{eV}^2)} \quad ,$$

and the characteristic measure of the proper evolution time in the rest frame of the neutrino system is proportional to ℓ/p. The sensitivity in Δm of any experiment is characterized both by ℓ/p and by statistics. The achievable value Δm^2 is typically

$$\Delta m^2 \simeq 2(N_e/N_x)^{1/4}\,(p/\ell\,\sin 2\xi)^{1/2}$$

for $N_e(N_x)$ observed events induced by ν_e and ν_x's. For maximal mixing ($\xi = 45°$), $p \sim 500$ MeV, and $\ell = 1.3\times 10^7$ m, the ultimate sensitivity of an atmospheric neutrino experiment is 2×10^{-3} eV. Figure 14 shows the sensitivity as a function of both ℓ and of $\cos\theta_z$. The $\cos\theta_z$ dependence is experimentally relevant since equal statistics come in equal intervals of

L. Sulak

LEPTON-NEUTRINO DIRECTION CORRELATION

Figure 18

CORRELATION OF CHARGED LEPTON WITH INITIAL NEUTRINO DIRECTION

I-M-B Nucleon Decay Facility 185

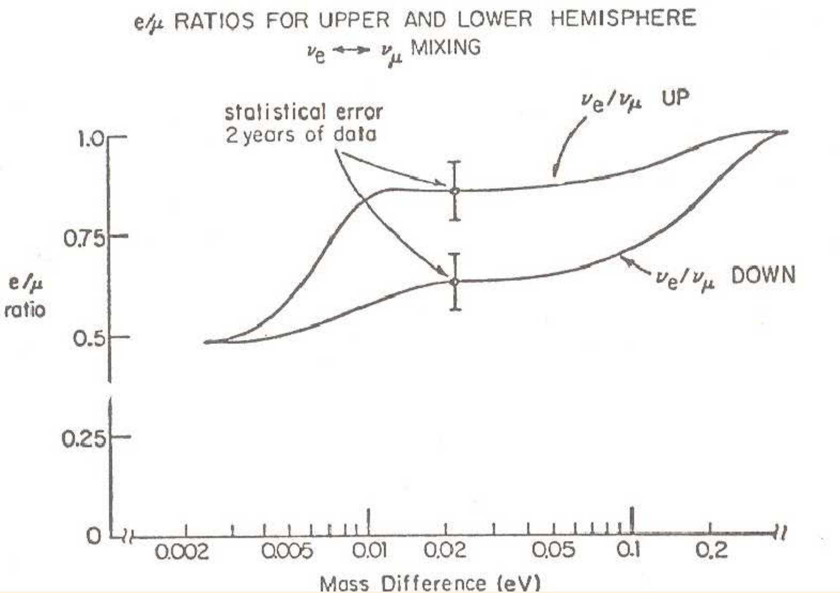
induced by ν_e (ν_μ). This rate is halved by the 0.3 GeV cut on charged lepton energy. Thus, for no oscillations, the e/μ event ratio should be 0.5 ± 0.07, whether initiated by down or up going neutrinos. Both down and up going e/μ ratios will be unity if ν_e, ν_μ oscillations exist with $L \lesssim 300$ km. The e/μ ratio will be unity only for upcoming neutrinos if $L \sim$ radius of the earth. And if muon neutrinos do not oscillate, but ν_e, ν_τ oscillations exist with a large mass difference, the e/μ event ratio will be 0.25 ± 0.04 for both up and down going events.

For e,μ oscillations, the sensitivity of the detector is characterized as a function of the mass difference in Fig. 20. The e/μ ratio is shown both for upward coming and downward going neutrinos. For two years of data the statistical power is ~four standard deviations for each ratio in the region between 0.006 eV and 0.15 eV. Thus, for e,μ mixing, the experiment is optimized in the low mass range, but the full 10 KT size of the detector is necessary to have sufficient statistical power.

e/μ RATIOS FOR UPPER AND LOWER HEMISPHERE $\nu_e \leftrightarrow \nu_\mu$ MIXING

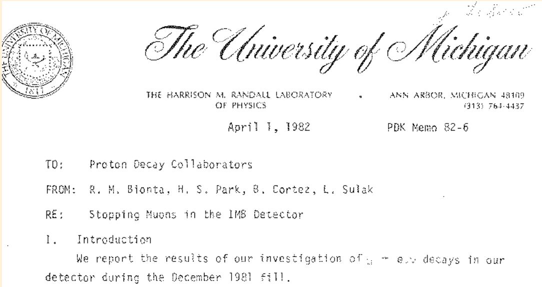
Figure 20

We should also consider the effect on vacuum neutrino oscillations induced by the different forward scattering amplitudes in the matter through which the upward coming neutrinos have passed. ν_e's can scatter from electrons by both neutral and charged currents, whereas ν_μ's and ν_τ's only have charge-current interactions. Wolfenstein has shown that both the vacuum Pontecorvo angles and the oscillation lengths are modified by the matter at oscillation lengths comparable to the earth's radius.[18] Since this results in exploring a somewhat different range of variables than in vacuum over the same distance, we ignore these effects in the current paper.


e/μ RATIOS FOR UPPER AND LOWER HEMISPHERE
νe ↔ νμ MIXING
statistical error
2 years of data
νe/νμ UP
νe/νμ DOWN
e/μ
ratio
1.0
0.75
0.5
0.25
0
0.002
0.005
0.01
0.02
0.05
0.1
0.2
Mass Difference (eV)

Preparation

- Calibration and performance monitoring with stopping muons (April 1982)



The University of Michigan

THE HARRISON M. RANDALL LABORATORY OF PHYSICS • ANN ARBOR, MICHIGAN 48109 (313) 764-4437

April 1, 1982 PDK Memo 82-6

TO: Proton Decay Collaborators

FROM: R. M. Bionta, H. S. Park, B. Cortez, L. Sulak

RE: Stopping Muons in the IMB Detector

I. Introduction

We report the results of our investigation of $\mu \to e\nu\nu$ decays in our detector during the December 1981 fill.

  - First measurement of μ decay with only 1/3 of detector filled.

- Additional Control of Systematics

- Use of real Gargamelle neutrino events
- Eventual use of BNL neon data and Argonne deuterium data
- Neutrino interaction models
- Large, convenient sample of stopping μ to calibrate the detector response to muon decay

The University of Michigan

THE HARRISON M. RANDALL LABORATORY OF PHYSICS • ANN ARBOR, MICHIGAN 48109
(313) 764-4437

PDK 83-103
July 18, 1983

TO: IMB Collaboration

FROM: Bill Foster

RE: The Making of the 5 Years Neutrino Background Tapes

- It has come to my attention the electron angular distributions from u-->evv decay are backwards (for muons from neutrinos) on this tape. This may have an effect on the fraction of observable u-->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.

Observation I

- Cortez and Foster September 1983 Harvard PhD theses
  - Proton decay to $e^+\pi^0$ and lepton K^0
  - 112 contained events in 130 days
  - 25 μ decays 22$\pm$4%. 33% expected
  - μ decay rate 2.5σ too low
  - No proton decay
- Shumard 1984 Michigan PhD thesis
  - Extensive study of detector μ decay response
  - Careful job of measuring and modeling the μ identification process
  - Included μ polarization, absorption, after-pulsing, ;ight reflection
  - 148 contained events in 202 days
  - 39 μ decays observed, 26.4$\pm$3.6% – 35% expected
  - μ decay rate 2.4σ too low

Observation II

- Blewitt 1985 Caltech PhD thesis
  - West coast data sample – 326 contained events in 417 days
  - μ decays were 2.8σ too low
- Lake Louise Meeting February, 1986
  - 26% of the 401 event IMB-1 sample have a μ decay
  - "If 40% of the ν_μ interactions do *not* result in a muon decay signal the observed value corresponds to ν_e/ν_μ of 1.3"
  - The expected value of ν_e/ν_μ is 0.64
  - Nusex reports $\nu_e/\nu_\mu = 0.28 \pm 0.11$
  - Kamioka reports $\nu_e/\nu_\mu = 0.38 \pm 0.08$

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[18)] and the Nusex detector[4)] can distinguish ν_e from ν_μ by shower development. They quote a ν_e/ν_μ 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 ν_e/ν_μ ratio with a number of assumptions about muon capture in water. If 40% of the ν_μ 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 ν_e/ν_μ ratio is still under active study. There is no directional dependence of the muon rate.

- IMB ν Anomaly Paper 1986

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

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. Svoboda, J. C. van der Velde, and C. Wuest

University of California, Irvine, Irvine, California 92717
University of Michigan, Ann Arbor, Michigan 48109
Brookhaven National Laboratory, Upton, New York 11973

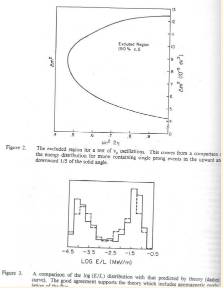
  - 401 event 417 day IMB-1 final data sample. 402 events expected.
  - 104 μ decays observed, 26$\pm$2% – 34$\pm$1% expected 3.5σ low.

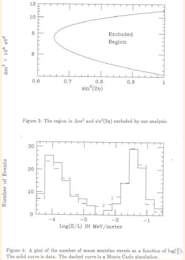
VOLUME 57, NUMBER 16 PHYSICAL REV

well not only globally but also in small regions. The simulation predicts that 34% $\pm$1% of the events should have an identified muon decay while our data has 26% $\pm$3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon ν's to electron ν'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. Any effect of this discrepancy has not been considered in calculating the nucleon-decay results.

- - Diversity of interpretation reflected the diverse opinions of the authors.
  - Deficit of decays was not mentioned in early drafts of the paper!
- Haines 1986 Irvine PhD thesis
  - Extensive study of neutrino interactions
  - Long version of the 1986 anomaly paper

Interpretation





- No Up/Down asymmetry
- No energy spectrum distortion
- E/L distributions as expected (in both IMB-1 and IMB-3)
- Event rate as expected
- Used this normality to publish limits on neutrino decay and matter effects as well as neutrino oscillation limits for $\Delta m^2 < 10^{-4}$ eV^2

Consternation

- M. Nakahata *et al.* J. Phys. Soc. Japan 1986
  - The Kamioka equivalent of IMB Haines *et al.* 1986
  - Atmospheric neutrino backgrounds for nucleon decay
  - No numbers for data
  - "Note the comparison is absolute. i.e. no normalization has been made"

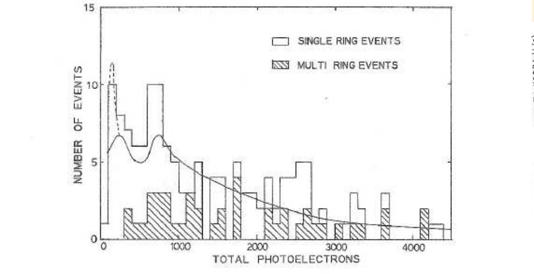


Fig. 17. The total photoelectron number distribution for the contained events. The histograms are the KAMIOKANDE data of 1.11 kton·years' exposure time. The solid and dashed lines are the calculated results of the neutrino Monte Carlo simulation. The dashed line includes the decay electrons of invisible low energy muons produced by ν_μ and $\bar{\nu}_\mu$ interactions. The peak at 700 p.e. is due to electrons produced by ν_e and $\bar{\nu}_e$. Note the comparison is absolute, i.e. no normalization has been made.

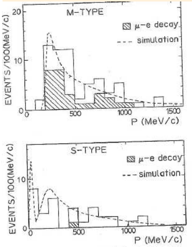


Fig. 20. The momentum distribution for M- and S-type single ring events. For M-type events, particles are assumed to be muons. The curves are the expectation of the neutrino Monte Carlo program. An excess in the distribution of S-type events at the low momentum is due to the decay electrons of invisible low energy muons produced by ν_μ and $\bar{\nu}_\mu$ interactions, corresponding to the dashed line in the Fig. 17.

- Same data as Kajita thesis

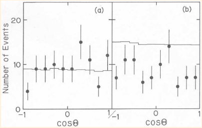
- T. Kajita PhD thesis Tokyo, February 1985 (UTICEPP-86-03 Feb. 1986)
  - 141 contained events in 474 days of Kamiokande detector (1.11 kt-yr)
  - Kamiokande M/S classification. Muons and showers
  - 97(89*) single prong. Expected 94(85*) (*$>$100 MeV/c)
  - 64 M type events. Expected 54
  - 33(25*) E type events. Expected 40(31*)
  - 29 muon decays when 39.3 expected. 2.4 σ low.
  - M type fraction 66.0$\pm$4.8%. Expected 57.5$\pm$2.4% 1.6 σ high.
  - the muon and electron fractions are as expected
  - None of these calculated significances appear in the thesis. They are mine.

Visit

- June 1986 visit to Tokyo, following Neutrino meeting in Sendai
  - Met with Koshiba and Kajita
  - Well received. Slurping noodles with Koshiba
  - Discussed the observed IMB μ decay deficiency. The IMB paper had just been submitted to PRL
  - Pointed out the discrepancies between M/S analysis and μ decay in Kamiokande work
  - Kind blank stares!
  - Assured that the M/S analysis was correct

- Kajita thesis data 1985 or 1986?
    - At SWOGU, April 1985, Koshiba showed a table similar to Kajita table 7-1
    - April 1985 table had 105(99*) event total, data through January 23, 1985, 349 days (0.84 kt-yr).
    - Kajita had 141(133*) event total, 474 days
    - Koshiba SWOGU talk "M-type ... a satisfactory agreement with the unnormalized expected distributions"
- Kajita's thesis was not unique. Kamiokande reported good agreement with expectations at many previous presentations and proceedings

Confirmation



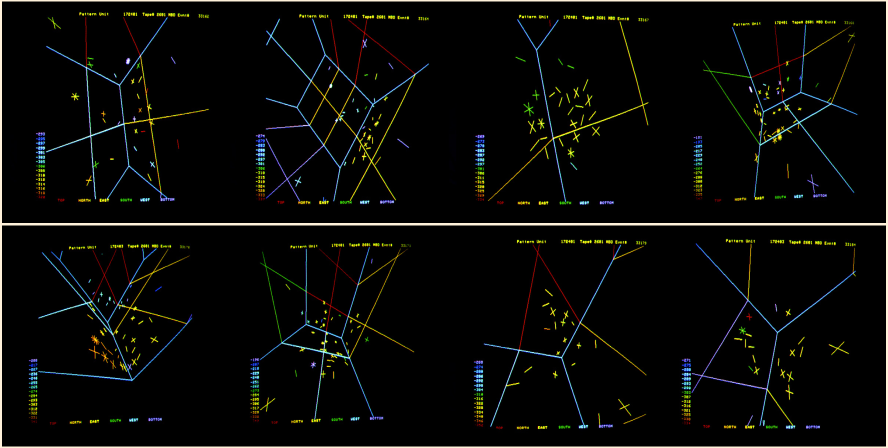
- 1988 Kamiokande paper
  - 277(265*) event 2.87 kt-yr exposure to Nov. 1987
  - Concluded a muon deficiency, 59%
  - the M/S classification had changed to agree with the μ decay rate.
  - Cites and quotes the IMB ν Anomaly Paper from 1986
- Interpretation still difficult since angular and energy distributions were as expected.

Source	Date	Exposure kt-yrs	Events	M type Obs/MC	Event Rate per kt-yr	Expected Event-rate
5'th WGU	1984	0.485	80	Agreed	165	Agreed
Arisaka Thesis	1985	0.661	84	1.03	127	129
6'th WGU	1985	0.84	99	1.13	118	111
Kajita Thesis	1986	1.11	133	1.19	120	108
Hirata *et al.*	1988	2.87	265	0.59	92	111

Changes

- Kamiokande I (1.11 kt-yr) 474 days 880 tons
- Kamiokande II (1.76 kt-yr) data added to Kamiokande I
- Timing added to the Kamiokande electronics
- University of Pennsylvania and B. Cortez joined
- Change of M/S algorithm to classify muons ... agree with muon decay rate.
- Serious neutrino rate drop from Kam I to Kam II.
  - Kam I 116$\pm$10 events/(kt-yr)
  - Kam II 77.3$\pm$6.8 events/(kt-yr)
  - IMB I 106$\pm$5 events/(kt-yr)
  - IMB 3 110$\pm$10 events/(kt-yr)

Distraction–SN1987A



8 Events in 6 seconds Messengers from 160,000 light years a way

IMB — 3.3 ($\rightarrow$ 5) kilotons of water at 50 kiloparsecs.

Next

- IMB-3 : 4 times the light collection
- M/S algorithms for IMB-3 ... 3 different ones.
- extend L/E to higher E. Upward entering muons
- Upward entering stopping muons.
- Uncontained events depended heavily on neutrino flux calculations. Integrate over a calculated neutrino spectrum and a varying fiducial mass.

Neutrino Flux

Interest in the Anomaly prompted more work on the atmospheric neutrino flux

- Volkova 1980 – High Energy no geomagnetic effects
- Gaisser and Stanev
- Lee and Koh
- Bugaev and Naumov
- Honda *et al.*

But all give μ/e $\approx$ 2 at contained energies.

Epilogue

SuperKamiokande (50 kt) merged IMB (8 kt) and Kamiokande (3 kt) collaborations

Larger volume much higher energy for contained events.

Higher event rate.

The neutrino anomaly was a strong motivation.

Chooz reactor experiment (not Double) closed the door on a $\nu_\mu \to \nu_e$ interpretation

Thanks

Thanks to Fred Reines, Maurice Goldhaber, Larry Sulak and Jack Van der Velde for their leadership
Thanks to Bruce Cortez, Geof Blewitt, Egbert Lehmann and numerous undergraduates for being part of my team
Thanks to Bill Foster, Eric Shumard and Todd Haines for adding pieces to the puzzle
Thanks to John Learned, Danka Kielezewska and Tegid Winn Jones for vivid insights.
Thanks to the rest of IMB for their collaboration.

Backup

What Did I Do?

- BNL E704 neutrino oscillations with 2 people.
- Little work on IBM proposal, I was working for C. Rubbia the competiton
- Joined IMB in Fall 1979
- Doubt about proton decay so I studied supernova response
- I designed and build the IMB DAQ and programmed about 1/2 of it.
- 2.7 events per second with online reconstruction. Saved upwards and contained. Saved fits. 32K PDP-11
- Did the first atmospheric neutrino oscillations analysis. Was not allowed to discover but could set limits in reduced fiducial volume.
- PRL and San Diego ICRC results (L/E distribution)
- Late summer 1985 I was convinced it was real.

- February 1986 confirmed my conclusion
- Spring 1986 tried to convince Kamiokande to publically confirm
- February 1987, supernova neutrinos
- IMB-3 work with many others.

Awards

- 2018 W.K.H. Panofsky Prize in Experimental Particle Physics
  Lawrence R. Sulak – Boston University
  "For novel contributions to detection techniques, including pioneering developments for massive water Cherenkov detectors that led to major advances in nucleon decay and neutrino oscillation physics."
- 2017 DPF Instrumentation Award
  Blair N. Ratcliff – SLAC
  Lawrence R. Sulak – Boston University
  "For the development of novel detectors exploiting the Cherenkov radiation to enhance the capabilities of frontier experiments devoted to the study of beauty and charm hadrons and atmospheric neutrinos."

- Supernova neutrinos
- Solar neutrinos
- Atmospheric neutrinos