The History of “Anomalous” Atmospheric Neutrino Events - Sulak Festschrift 2005

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Physics Department
University of Notre Dame

October 22, 2005

Caveats

- I am not an historian
- I am not unbiased
- I was a participant
- Sources
  - Journal Articles
  - Conference Proceedings
  - Theses (PhD and other)
  - Internal reports and Memos
  - Correspondence including Emails
  - Notes
  - Memory!
- Selection Effect

Outline

- Scientific Context
- Inspiration
- Formulation
- Preparation
- Observation
- Interpretation
- 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 $\overline{\nu_e}$ Mass
  - Pasierb et al. $\nu D \to \nu PN$ Reactor ν Oscillations

Inspiration I

- Discovery of the τ
- Mann and Primikoff 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 idea of ν oscillations to > 2 flavors
  - Inspired Renaissance in the subject
  - Inspired by the possibility of "right handed current" from the high y anomaly!
  - Long baseline ideas in this paper also inspired studies of matter effects
  - Mentions CP violation possibilities

- Maturation of accelerator neutrino physics

Inspiration II

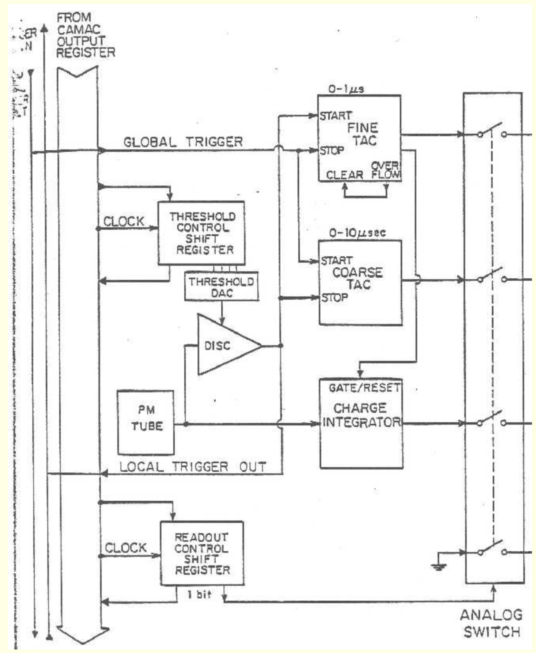
- Asymptotic Freedom
- Grand Unified Theories – SU(5)
- Baryon Instability
- Super-symmetric Grand Unification and $\mu^+ K^0$
- Very Large, but feasible detectors
- Neutrino Induced Backgrounds to Proton Decay

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

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



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

A LONG BASELINE NEUTRINO OSCILLATION EXPERIMENT SENSITIVE TO

MASS DIFFERENCES OF HUNDREDTHS OF AN ELECTRON VOLT[#]

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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

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L. Sulak

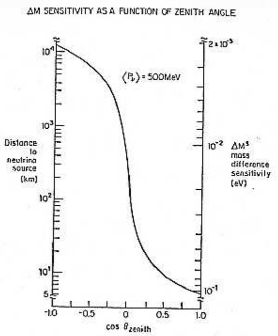


Figure 14

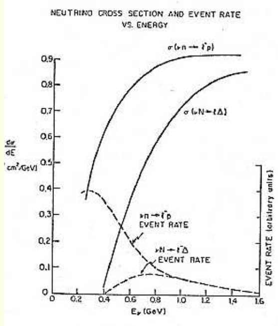


Figure 15

I-M-B Nucleon Decay Facility

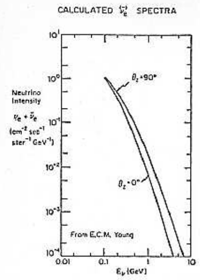


Figure 16

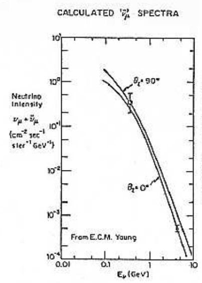


Figure 17

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

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

which is familiar from the two component evolution of the $K^\circ - \bar{K}^\circ$ syste[...] 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 [...] of the neutrino system is proportional to ℓ/p. The sensitivity in Δm [...] experiment is characterized both by ℓ/p and by statistics. The achiev[...] value Δm^s is typically

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

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

L. Sulak

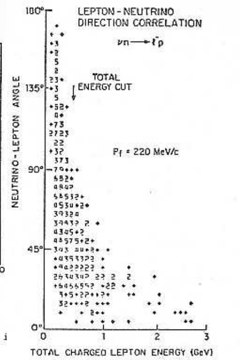
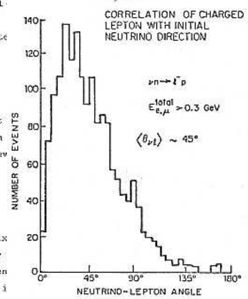


Figure 18



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.

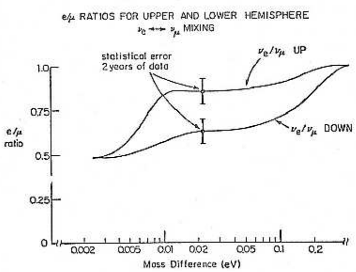
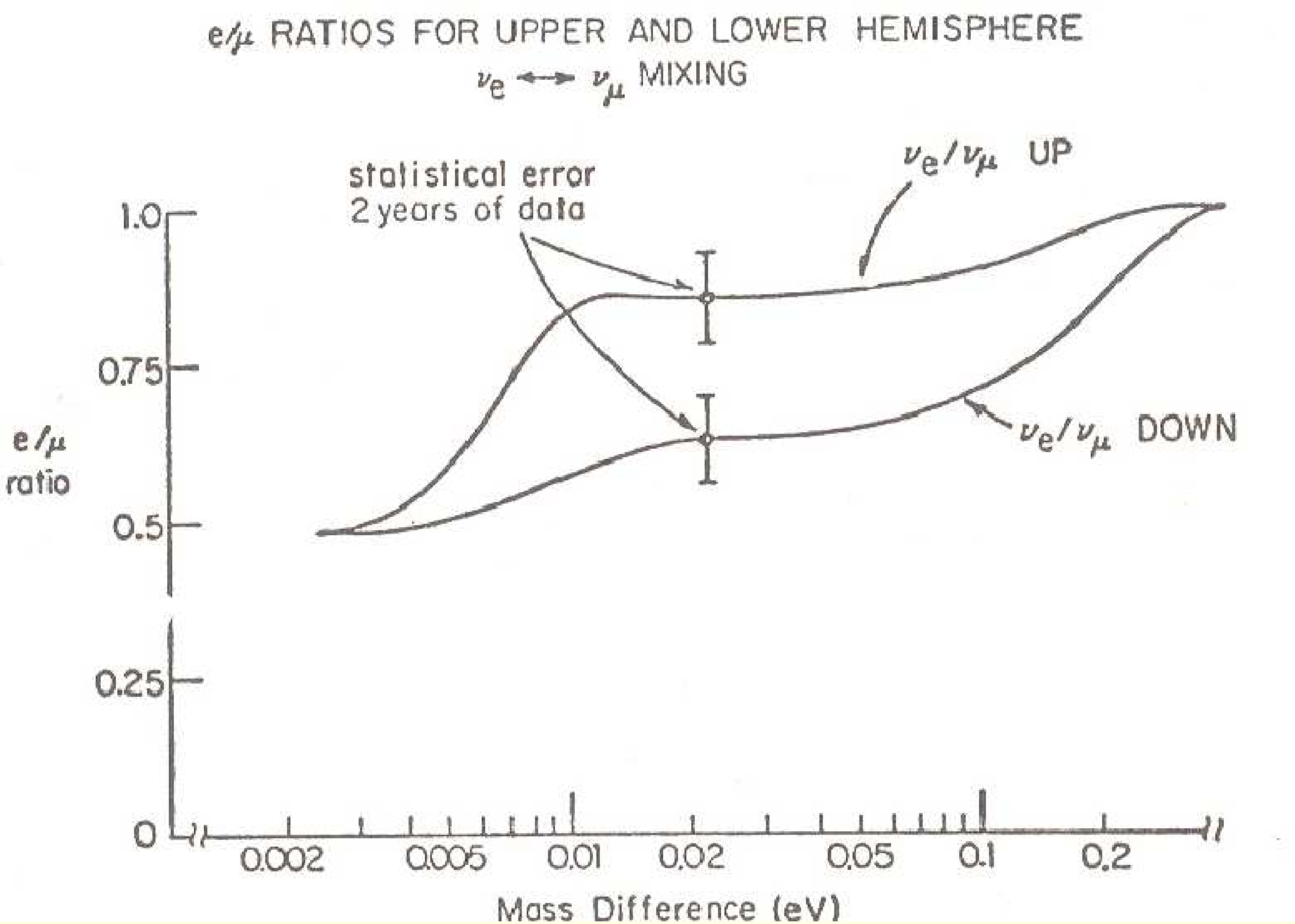


Figure 20

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
$\nu_e \leftrightarrow \nu_\mu$ MIXING
statistical error
2 years of data
ν_e/ν_μ UP
ν_e/ν_μ DOWN
1.0
0.75
0.5
0.25
0
e/μ
ratio
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 measurements 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

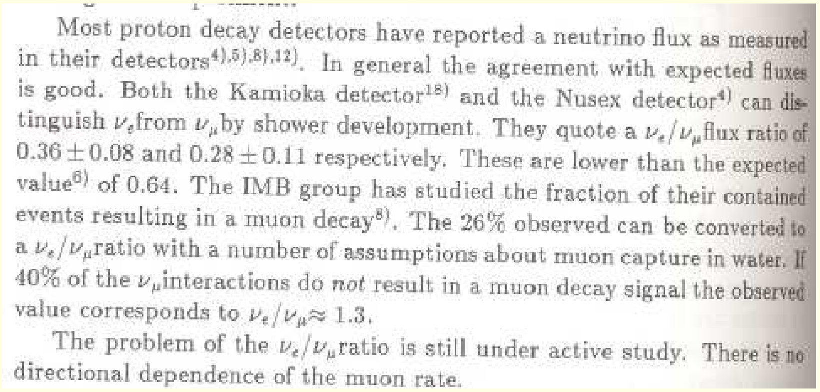
- It has come to my attention the electron angular distributions from u-->evv decay are backwards (for muons from neutrinos) on this tape. This may have an effect on the fraction of observable u-->e decays, which Bruce says is somewhat higher than the data. This may be corrected in a future release when 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$4%. 33% expected
  - μ decays rate 2.5σ too low
  - No proton decay
- Shumard 1984 Michigan PhD thesis
  - Extensive study of detector μ decay response
  - Careful job of measuring and modeling the μ identification process
  - Included μ polarization, absorption, after-pulsing, light reflection
  - 148 contained events in 202 days
  - 39 μ decays observed, 26.4$\pm$3.6% – 35% expected
  - μ decays rate 2.4σ too low

Observation II

- Blewitt 1985 Caltech PhD thesis
  - West coast data sample – 326 contained events in 417 days
  - μ decays rate 2.8σ too low
- Lake Louise Meeting February, 1986
  - 26% of 401 event IMB-1 sample have 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 $\nu_e/\nu_\mu = 0.36 \pm 0.08$



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

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

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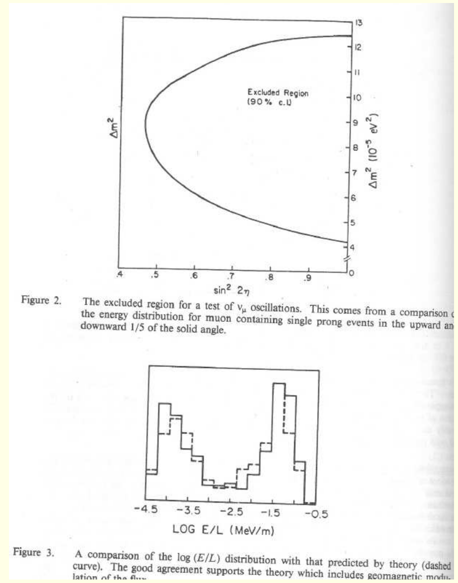
well not only globally but also in small regions. The simulation predicts that 34% ± 1% of the events should have an identified muon decay while our data has 26% ± 3%. This discrepancy could be a statistical fluctuation or a systematic error due to (i) an incorrect assumption as to the ratio of muon 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.

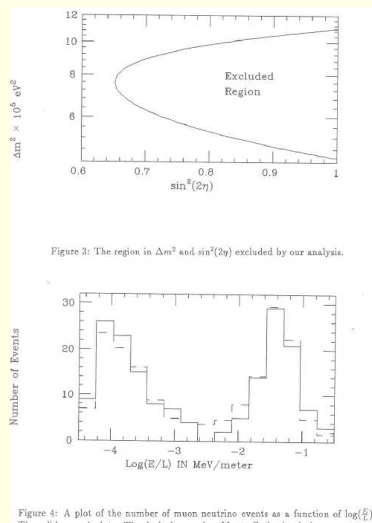
– Diversity of interpretation reflected the diverse opinions of the authors.
– Deficit of decays was not mentioned in early drafts of the paper!

- 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"

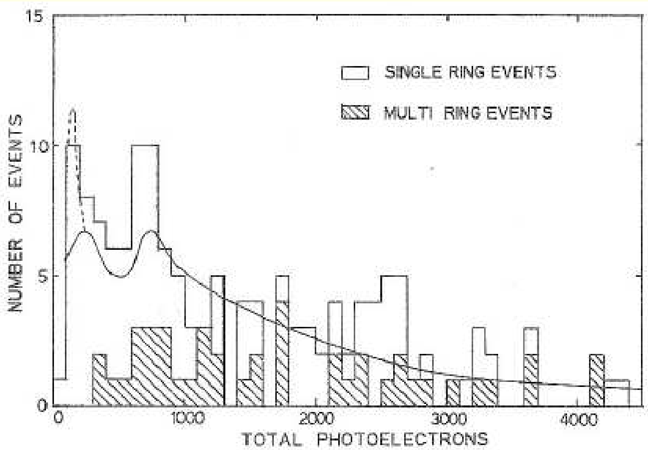


Fig. 17. The total photoelectron number distribution for the contained events. The histograms are the KAMIOKANDE data of 1.11 kton·years' exposure time. The solid and dashed lines are the calculated results of the neutrino Monte Carlo simulation. The dashed line includes the decay electrons of invisible 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.

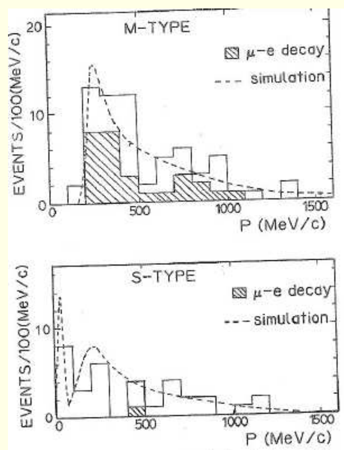


Fig. 20. The momentum distribution for M- and S-type single ring events. For M-type events, particles are assumed to be muons. The curves are the expectation of the neutrino Monte Carlo program. An excess in the distribution of S-type events at the low momentum is due to the decay electrons of invisible 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 event 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.
  - Conclusion the muon and electron fractions are as expected.
  - None of these calculated significances appear in the thesis.

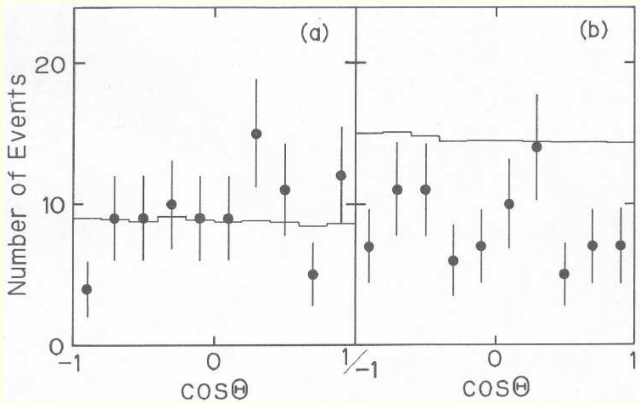
- June 1986 visit to Tokyo, following Neutrino meeting in Sendai
  - Met with Koshiba and Kajita
  - Well received. Slurping noodles with Koshiba!
  - Discussed the observed IMB μ decay deficiency. The IMB paper had just been submitted to PRL
  - Pointed out the discrepancies between M/S analysis and 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	0.840	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

Epilogue

- Rate Drop in Hirata et al., 1988?
  - 2.87 kt-yr was the sum of Kamioka 1 (1.11 kt-yr) and Kamioka II (1.76 kt-yr) exposure.
  - Notes: "Why such a dramatic drop?"
  - Email to Totsuka April 18, 1989
  - Response August 12, 1989: Refit of Kamioka 1 had an event rate of "116±9.4 events/ktonyr". Both Kamioka 1 and Kamioka 2 had rates which agree with expectations.
  - By subtraction this gives an event rate for Kamioka II of 77.3±6.8 per kt-yr

Kajita
Kamioka 1 $\frac{133 \text{ events}}{474 \text{ days} \quad 880 \text{ kt}} = 116 \pm 10$ /kt-y
Pe >
Atmos ν
Kamioka 1+2 $\frac{265}{2.87} = 92.3 \pm 5.7$
Why such a dramatic drop.

With the above (main) reasons, we expect larger number of events per ktonyr in Kam-I. The larger number of Kam-I events is reasonably reproduced by the MC simulation:

$$\frac{\dfrac{(number\ of\ events)_{data}}{(number\ of\ events)_{MC}}_{KAM-I}}{\dfrac{(number\ of\ events)_{data}}{(number\ of\ events)_{MC}}_{KAM-II}} = 1.17 \pm 0.12$$

- IMB 1 event rate was 106±5 per kt-yr. IMB 3 rate (in the notes – only 1.53 kt-yr) was 110±10 per kt-yr (E>140 MeV).