Atmospheric Neutrinos:
from the Pioneering Experiments to Kamiokande

Paolo Lipari
INFN Roma “Sapienza”

History of the Neutrino

Paris: September 5th, 2018
First Detection

Proton Decay Experiments

“Anomaly”

“Hint for New Physics”

“Evidence for Neutrino Oscillations”

Established results in physics textbooks.
At this conference:

John Learned
“The Saga of atmospheric neutrinos”.
September 5, 15:05

Takaaki Kajita
“Atmospheric neutrinos: the anomaly becomes the discovery”
September 6, 16:40

Christian Spiering
“High energy neutrinos and neutrino telescopes”
September 7, 14:45

Posters:

John LoSecco: “Discovery of the atmospheric neutrino anomaly"

Francesco Ronga: “Neutrino Oscillations: personal recollections
Focused before the Kajita's talk 1998”

Igor Zheleznyk: “The Soviet DUMAND program and the development of alternative large scale neutrino telescopes”
Viktor HESS (1912)

The beginning of “High Energy Astrophysics” the discovery of Cosmic Rays
Birth of Particle Physics
Interpretation of Cosmic-Ray Measurements Far Underground

PAUL H. BARRETT, LOWELL M. BOLLINGER, GIUSEPPE COCCONI, YEHUDA EISENBERG, AND KENNETH GREISEN
Cornell University, Ithaca, New York

Reconstruct the Cosmic Ray spectrum
Flux of Atmospheric Neutrinos

Cosmic Ray Showers in the Earth Atmosphere

\[ p + \text{Air} \rightarrow p \ n, \ \pi^+ \pi^- \pi^0 \ K^+ \ K^- \ K^0 \ \bar{K}^0 \ \ldots \]

\[ \pi^+ \rightarrow \mu^+ \ \nu_\mu \]

\[ \rightarrow \bar{\nu}_\mu \ e^+ \ \nu_e \]
There *must be* a flux of “cosmic neutrinos” [atmospheric neutrinos]

**Is it detectable?**

Are there (high energy) neutrinos Generated from astrophysical Sources ?

**Is Neutrino Astronomy Possible?**
M. Markov, **1960**: We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.
“Visionaries” in the Soviet Union


Fascinating review by a key participant:

I. Zheleznykh,
“Early years of high-energy neutrino physics in cosmic rays and neutrino astronomy (1957-1962),”

[Poster here]

K. Greisen, “Cosmic ray showers,”
Neutrino Induced Muons

\[ \nu_\mu + N \rightarrow \mu^- + \ldots \]

\[ \bar{\nu}_\mu + N \rightarrow \mu^+ + \ldots \]
The first observations of Atmospheric Neutrinos

C. V. Achar et al.,
“Detection of muons produced by cosmic ray neutrinos deep underground,”

F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, G. R. Smith, J. P. F. Sellschop and B. Meyer,
“Evidence for high-energy cosmic ray neutrino interactions,”
M. G. K. Menon, P. V. Ramana Murthy, B. V. Sreekantak and S. Miyake,
"Cosmic-ray intensity at great depths and neutrino experiments,"

In early 1963 great excitement gripped Fred Reines “Neutrino Group” at the Cae Institute of Technology. Fred recognized that a PhD thesis of P.V.Ramana Murthy of the Tata Institute of Fundamental Research, Bombay showed that at depth attainable in the mines of the Kolar Gold Field in Southern India it might be possible for him and its group to carry out an experiment of which he had long dreamed.
William R. Kropp, Mildred M. Rie, Linda Price,
“Neutrinos and other Matters: Selected works of Frederick Reines’,”
World Scientific (1991)

William R. Kropp and Marshall F. Crouch,
“Some reminiscences of the CWI Atmospheric Neutrino Experiment”.

[...] The mines couldn’t make much sense of our efforts to detect neutrinos. After many attempts at understanding out activities they gave up and dubbed us “Goggafangers” – literally the bug catchers. Fred [Reines] of course had a special title, he was the “Makulu Bass Goggafanger”, the Big Boss Bug Catcher.

[...] As might be imagined, politics were an ever present issue throughout the duration of the experiment (1963–1971). [...] troubling political problem were a continuing feature of the experiment both is South Africa and on our university campuses.
Fig. 9 Zenith angle distribution of events in the ERPM experiment, South Africa.
T. D. Lee, C. N. Yang and P. Markstein,
“Production Cross-section of Intermediate Bosons by Neutrinos in the Coulomb Field of Protons and Iron,”

\[ \nu_\mu + Z \rightarrow \mu^- + W^+ + Z \]
\[ L = -R_\oplus \cos \theta_z + \sqrt{R_\oplus^2 \cos^2 \theta_z + 2hR_\oplus + h^2} \] 

\[ \langle h \rangle \approx 20 \text{ Km} \]

\[ L = 2R_\oplus |\cos \theta_z| \]

\[ \approx 12,700 |\cos \theta_z| \text{ km} \]

\[ \cos \theta_z < 1 \]

\[ L = \sqrt{2hR_\oplus} \approx 500 \text{ Km} \]

\[ \cos \theta \approx 0 \]

\[ L = \frac{h}{\cos \theta_z} \approx \frac{20}{\cos \theta_z} \text{ Km} \]

\[ \cos \theta_z > 1 \]
(b) intensity relative to that at $90^\circ$, as a function of energy


The neutrino cross section in 1971
\[ M_W = \left( \frac{1}{3} m_p E_S \right)^{1/2} \]
Study of the neutrino cross section

$0.02 \lesssim M_w^{-1} \lesssim 0.35 \ (\text{GeV/c}^2)^{-1}$

$45 \gtrsim M_w \gtrsim 2.9 \ (\text{GeV/c}^2)$
# Neutrino Astronomy!

[celestial coordinates of the directions of interesting events]

## Table III

A listing of the category 1A and 1B events which have been attributed to neutrinos and used in our calculation. Included is the time, location in array, energy deposition, and sidereal coordinates.

<table>
<thead>
<tr>
<th>Date</th>
<th>G.M.T.</th>
<th>Elements</th>
<th>Energy deposition (MeV)</th>
<th>Right ascension (deg)</th>
<th>Declination (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Feb. 1965</td>
<td>20:47</td>
<td>E4L</td>
<td>29</td>
<td>219.9 ± 12.9</td>
<td>7.3 ± 7.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W4L</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 Feb.</td>
<td>23:20</td>
<td>E5M</td>
<td>55</td>
<td>119.1 ± 11.9</td>
<td>13.3 ± 9.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W5U</td>
<td>118</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 Mar.</td>
<td>17:52</td>
<td>E4L</td>
<td>19</td>
<td>58.9 ± 11.5</td>
<td>50.9 ± 9.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W4L</td>
<td>16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 Apr.</td>
<td>13:15</td>
<td>E2M</td>
<td>24</td>
<td>13.1 ± 13.0</td>
<td>43.2 ± 10.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2M</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 June</td>
<td>21:36</td>
<td>E1L</td>
<td>22</td>
<td>326.6 ± 12.6</td>
<td>11.6 ± 7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W2L</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 June</td>
<td>00:41</td>
<td>E4U</td>
<td>8</td>
<td>176.8 ± 11.8</td>
<td>8.0 ± 8.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W4M</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 July</td>
<td>14:19</td>
<td>E3M</td>
<td>19</td>
<td>255.2 ± 11.4</td>
<td>27.7 ± 5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W3U</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 Nov.</td>
<td>14:06</td>
<td>E4L</td>
<td>Large</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td>W4L</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Neutrino detector in a Utah salt mine.

Fast timing (versus of muon)
Magnetized Iron

Shallow depth 1500 m.w.e.
only up-going (nu-induced) muons

603 days live time

$10^6$ down going muons

5 up-going muons

(spectrum !)

$1\sigma$, $2\sigma$, and $3\sigma$

$E_0 > 320, 80, \text{ and } 29 \text{ GeV}$

$M_W > 10, 5, \text{ and } 3 \text{ GeV}$
Baxsan Neutrino telescope
MACRO detector at Gran Sasso
PROTON DECAY
Conservation of the Number of Nucleons*

F. Reines and C. L. Cowan, Jr., University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

and

M. Goldhaber, Brookhaven National Laboratory, Upton, New York

(Received September 27, 1954)

It has often been surmised that there exists a conservation law of nucleons, i.e., that they neither decay spontaneously nor are destroyed or created singly in nuclear collisions.¹ In view of the fundamental nature of such an assumption, it seemed of interest to investigate the extent to which the stability of nucleons could be experimentally demonstrated.²

To investigate the possible decay of a free proton, the large scintillation detector developed for the neutrino search³ was employed. The detector was partially shielded from cosmic rays by placing it in an underground room with about 100 feet of rock above.

First limit: $10^{21}$ yr

The data give no evidence for the existence of nucleon decay. Lower limits on the half-life of the nucleon from $2 \times 10^{28}$ to $8 \times 10^{29}$ yr depending on the assumed decay mode are established. It is seen that the atmospheric muon neutrino serves as the major source of background in the present experiment. If it were possible to positively identify all muon neutrino events, improved half-life limits could be established.
J. C. Pati and A. Salam,
“Is Baryon Number Conserved?,”

H. Georgi and S. L. Glashow,
“Unity of All Elementary Particle Forces,”

H. Georgi, H. R. Quinn and S. Weinberg,
“Hierarchy of Interactions in Unified Gauge Theories,”
IMB DETECTOR
2048 PM TUBES

MAX. DIMENSIONS

22.5 m
17 m
18 m
NUSEX: contained events
The “Anomaly"
Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search


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*Brookhaven National Laboratory, Upton, New York 11973*
*Cleveland State University, Cleveland, Ohio 44115*
*University of Hawaii, Honolulu, Hawaii 96822*
*University of Notre Dame, Notre Dame, Indiana 46556*
*University College, London WC1E 8BT, United Kingdom*
*Warsaw University, Warsaw PL-00-681, Poland*
(Received 6 June 1986)

We have developed an extensive model of atmospheric $\nu$ interactions which provide the backgrounds to nucleon-decay experiments. We report results from a 417-live-day exposure of the Irvine-Michigan-Brookhaven detector. During this time 401 contained events were observed at a rate and with characteristics consistent with atmospheric $\nu$ interactions. We have calculated the expected backgrounds to a variety of two- and three-body decay modes and have set lower limits on many nucleon partial lifetimes.
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 \(\nu\)'s to electron \(\nu\)'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.

T. J. Haines et al. [IMB Collaboration]  
“Calculation of Atmospheric Neutrino Induced Backgrounds in a Nucleon Decay Search,”  

Fig. 19
EXPERIMENTAL STUDY OF THE ATMOSPHERIC NEUTRINO FLUX

K.S. HIRATA, T. KAJITA, M. KOSHIBA, M. NAKAHATA, S. OHARA, Y. OYAMA, N. SATO, A. SUZUKI, M. TAKITA, Y. TOTSUKA
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Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

and

B.G. CORTEZ
AT&T Bell Laboratories, Holmdel, NJ 07922, USA

Received 25 January 1988

We have observed 277 fully contained events in the KAMIOKANDE detector. The number of electron-like single-prong events is in good agreement with the predictions of a Monte Carlo calculation based on atmospheric neutrino interactions in the detector. On the other hand, the number of muon-like single-prong events is $59 \pm 7\%$ (statistical error) of the predicted number of the Monte Carlo calculation. We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes.
Fig. 1. Momentum distributions for: (a) electron-like events and (b) muon-like events. The last momentum bin sums all events with their momenta larger than 1100 MeV/c. The histograms show the distributions expected from atmospheric neutrino interactions.

Fig. 2. 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.
Fig. 4. The allowed neutrino oscillation parameters at 90% CL from the Kam-I–II data, for the case of $\nu_\mu \leftrightarrow \nu_e$ (left), and $\nu_\mu \leftrightarrow \nu_\tau$ (right). The best fit parameter sets are shown by crosses. The two open circles in the figure for $\nu_\mu \leftrightarrow \nu_\tau$ indicate the points which are used in figs. 2 and 3. All the other experimental results [13,22–24] show excluded regions.
R. Becker-Szendy et al., [IMB Collaboration]  
“A Search for muon-neutrino oscillations with the IMB detector,”  

Muon neutrinos produced as a result of cosmic-ray interactions with the atmosphere are used to search for $\nu_\mu$ oscillations into $\nu_\tau$ by comparing the measured rate of upward-going muons in the Irvine-Michigan-Brookhaven detector with the expected rate. In addition, the ratio of upward-going muons which stop in the detector to those which exit is used to search for deviations from the expected spectrum. This latter technique is free of flux and cross-section normalization uncertainties. No evidence for oscillations is found. 90% C.L. limits on $\delta m^2$ are derived in the range $(1-2) \times 10^{-4} \text{ eV}^2$ for $\sin^22\theta > 0.5$. 

**IMB**  
and  
up-going muons
Systematic errors
[in experiment or in the predictions]

or

NEW PHYSICS ?
\[ \dot{N}_{\nu, \text{events}} = \]

\[ \phi_{CR}(E_0) \otimes \begin{bmatrix} \text{Solar Modulations} \\ \text{Geomagnetic effects} \end{bmatrix} \]

\[ \otimes \sigma_{p \text{Air}\rightarrow \pi^{\pm},K^{\pm},0} \otimes \begin{bmatrix} \text{Weak Decays} \\ \text{Shower Calculation} \end{bmatrix} \]

\[ \otimes \sigma_{\nu A}(E_{\nu}) \otimes \begin{bmatrix} \text{Detector Properties} \end{bmatrix} \]
\[ \dot{N}_{\nu, \text{events}} = \phi_{\text{CR}}(E_0) \times \text{[Solar Modulations]} \times \text{[Geomagnetic effects]} \]

\[ \times \sigma_{p \text{Air} \rightarrow \pi^\pm, K^\pm, 0} \times \text{[Weak Decays]} \times \text{[Shower Calculation]} \]

\[ \times \text{[Neutrino Propagation]} \]

\[ \times \sigma_{\nu A}(E_{\nu}) \times \text{[Detector Properties]} \]
Calculations of the Atmospheric Neutrino Flux

T. K. Gaisser and M. Honda,
“Flux of atmospheric neutrinos,”
[hep-ph/0203272].
Main channel for Atmospheric neutrinos

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]
\[ \rightarrow \bar{\nu}_\mu e^+ \nu_e \]

+ Charge conjugate channel

1. Robust “relation” between muon and electron neutrinos
   [Generated by the same source]

2. Possibility of “monitoring” of the neutrino beam using muons.

3. Up-Down symmetry
Neutrino Flavor Ratio

\[
\frac{\nu_e + \bar{\nu}_e}{\nu_\mu + \bar{\nu}_\mu}
\]
Solar Modulations

![Graph showing solar modulations with different data points and curves.]
Relativistic charged particles. [Latitude effect]

Mostly protons (+ ionized nuclei) [East-West effect]
Geomagnetic effects

The (4pi) sky over the Kamiokande site
Rigidity \([p/q]\) cutoff
along the neutrino direction

![Diagram showing geomagnetic effects with contour lines and a map of the Earth's horizon.](image-url)
Geomagnetic effects

The \((4\pi)\) sky over the Kamiokande site

Rigidity \([p/q]\) cutoff along the neutrino direction

\[ \text{number of events} \]

\[ \text{number of events} \]

East-West effect
Modeling of hadronic Interactions
[Spectra of final state particles]
(largest source of uncertainty)

\[ p + ^{16}\text{O} \rightarrow \pi^\pm + \ldots \]
Calibrate the atmospheric neutrino calculation with *muon observations*
**Difficulty:** Most of the muons that are more “intimately associated” with GeV neutrinos do not reach the surface of the Earth (because they *decay in flight*).

**Solution:** Measure the muons at high altitude [balloon measurements during the travel to the stratosphere]

![Growth curves for 1 GeV $\mu^+$ and $\mu^-$](image)

![Measurements at “float altitude”](image)
The “Muon Polarization crisis” (1998)

[Muons created in a well defined spin state]

\[ R_\pi \equiv \frac{\Gamma(\pi^+ \to e^+ + \nu_e)}{\Gamma(\pi^+ \to \mu^+ + \nu_\mu)} = \left( \frac{m_e}{m_\mu} \right)^2 \left( \frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2} \right)^2 = 1.28 \times 10^{-4} \]
“3-Dimensional” versus “1-Dimensional”

1D: Neutrino collinear with primary Cosmic Ray
Alternative interpretations of the “atmospheric neutrino problem”

Proton decay  \[ p \rightarrow e^+ \nu \nu \]

Neutrino Decay

Oscillations into sterile neutrinos

Flavor Changing  Neutral Currents

Violations of Equivalence Principle
The doubts of theorists and of the "Physics Community"
G. Altarelli,
“Neutrino masses: A Theoretical introduction,”
CERN-TH-7315-94.
In Proc. 6th International Symposium on Neutrino Telescopes
22-24 Feb 1994. Venice, Italy

There are data from Kamioande and IMB3 on the ratio \((\nu_\mu/\nu_e)_{\text{Data}}/(\nu_\mu/\nu_e)_{\text{MC}}\) that indicate a deficit of \(\nu_\mu\) with respect to Monte Carlo. Other less precise experiments (Frejus, NUSEX) do not confirm these findings. If interpreted as a real effect due to \(\nu_\mu-\nu_e\) or \(\nu_\mu-\nu_\tau\) oscillations the data would imply \(\Delta m^2 \geq 10^{-3} \text{ eV}^2\) with \(\sin^2 2\theta\) large (0.5, 1).

This evidence does not appear to be really compelling so far. I will keep these results in mind, but I will put them aside waiting for a clear-cut experimental clarification.

... Large Mixing angles are “unpalatable” ....
J. R. Ellis,
“Supersymmetry and grand unification,”

Abstract:
Supersymmetry and Grand Unification are the two most promising directions for physics beyond the Standard Model. They receive indirect experimental support from the apparent lightness of the Higgs boson, the values of the gauge couplings measured at LEP and elsewhere, and the persistent solar neutrino deficit.

[.....]

As reviewed here by Winter, there are other suggestions of mass and oscillations effects in atmospheric neutrinos and the LSND experiment, but I prefer to wait and see whether these claims are confirmed.
O. G. Ryazhskaya,
"Is there an excess of electron-neutrinos in the atmospheric flux?,”
JETP Lett. 60, 617 (1994).

O. G. Ryazhskaya,
“Comment on an interpretation of measurements of the flux of atmospheric neutrinos by the Kamiokande detector,”

**FIG. 1.** Two-dimensional $R^2-Z$ distribution of the interaction points and momentum directions for events detected by the Kamiokande detector. a) Fully contained (FC) events; b) partially contained (PC) events. $Z$—Vertical axis; $R$—distance along the radius of the cylindrical working volume; filled circles—interaction points for electron-like events; open circles—the same, for muon-like events. The vertical and horizontal lines are the boundaries of identical volumes (see the text proper).
The “Flesh and Blood” of experiments
P. Galison,
“How the First Neutral Current Experiments Ended,”

One might call this second stage of experiment-theory interaction a process of reinforcement.

the flesh and blood of the experiment

Only gradually were the various individual arguments transformed into the kind of evidence finally assembled for publication. Little by little, the conclusion was reinforced by the many studies necessary to assess the background. Certainly no one moment can be pointed to either in E1A or in Gargamelle that could be called the instant of discovery.
The resolution of the “Anomaly” into “Evidence”

What was necessary was the extension of the domain in L and E of the observations.

What emerged was an ensemble of deviations from the “standard” prediction. With a “structure” (in energy, zenith angle) could reveal the properties of the new physics.

The results had a consistent interpretation in terms of a new physical concept [Neutrino Oscillations].

Witnessing this “process” in real time has reinforced my confidence in the “scientific method”.