Atmospheric Neutrino Oscillations

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• Introduction: Kamiokande - the starting point of my research -
• Discovery of neutrino oscillations: History
• Discovery of neutrino oscillations
• Recent result and a remark on the future
• Summary

(No introduction to neutrino oscillation and related physics... Sorry for this.)
Introduction:

Kamiokande
- the starting point of my research —
Proton decay experiments (1980’s)  

Grand Unified Theories (in the 1970’s) $\Rightarrow \tau_p = 10^{30\pm2}$ years

These experiments observed many contained atmospheric neutrino events (background for proton decay).
Kamiokande
3kton water Cherenkov detector (fiducial mass ~ 1kton)

1983 (Kamiokande construction)
Discovery of neutrino oscillations: History
A new particle identification (PID) software for multi Cherenkov-ring events. Namely, I designed that the PID can identify if a Cherenkov ring of a multi Cherenkov-ring event is a non-showering (muon-like) or showering (electron-like) whenever possible.

The simplest application of the PID was on single Cherenkov-ring events....
Particle identification: electron or muon?

- **electron-like** event
- **muon-like** event

Kamiokande

- **e**: electromagnetic shower, multiple Coulomb scattering
- **μ**: propagate almost straightly, loose energy by ionization loss

Particle types are identified using the difference in the event pattern (maximum likelihood method)
Production of atmospheric neutrinos
$\nu_\mu$ over $\nu_e$ ratio of the beam

$(\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$

$\nu_\mu$ over $\nu_e$ ratio is calculated to an accuracy of about 2% below $\sim 5$GeV.

M. Honda et al., PRD 83, 123001 (2011)
After more than 1 year of studies, we concluded that the muon deficit cannot be due to any major problem in the data analysis nor in the Monte Carlo simulation.

**Paper conclusion:** “We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data.”

First supporting result on small $\mu/e$

IMB experiment also reported smaller ($\mu/e$) in 1991 and 1992.
After the first result on the $\mu/e$ ratio ...

• Although it was clear that the small $\mu/e$ ratio implied something unexpected, the physics behind this result was unknown. (We recognized that neutrino oscillation was a possibility as we wrote in the paper.)

  – Was the result due to neutrino oscillations?
  – If so, $\nu_\mu \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_\tau$?
  – Some other physics?
What will happen if the muon deficit is due to neutrino oscillations

$\nu_\mu \rightarrow \nu_\tau$ oscillation

Detect down-going and up-going $\nu$

One should observe a deficit of upward going $\nu_\mu$'s (=muons)!
Angular correlation

Events with their energy larger than $\sim 1$ GeV need to be observed to study the zenith angle dependence.
Zenith angle

Up/down flux ratio is very close to 1.0 and accurately calculated (1% or better) above a few GeV.
multi-GeV events

Deficit of upward-going μ-like events

\[
\frac{Up}{Down} = 1.38^{+0.39}_{-0.30} \quad \frac{Up}{Down} = 0.58^{+0.13}_{-0.11} \quad (2.9\sigma)
\]

Not high enough statistics to conclude ...
Much higher statics required (= much larger detector required)
Discovery of Neutrino Oscillations
Super-Kamiokande detector

50,000 ton water Cherenkov detector
(22,500 ton fiducial volume)

11200 PMTs (Inner detector)
1900 PMTs (Outer detector)

1000m underground

Atmospheric Neutrino Oscillations
Water filling in Super-Kamiokande

Jan. 1996
Super-K detector construction

Aug. 1995
Fully automated analysis

- One of the limitation of the Kamiokande’s analysis was the necessity of the event scanning for all data and Monte Carlo events, due to no satisfactory ring identification software.

Hough transformation + maximum likelihood

Super Kamiokande I 1489.2 days

Multi Cherenkov ring event

FC (fully contained)
Various types of atmospheric $\nu$ events (1)

**FC (fully contained)**

- **Color:** timing
- **Size:** pulse height

**Single Cherenkov ring muon-like event**

- $E_\nu \sim 1\text{GeV}$

**Multi Cherenkov ring event**

- $E_\nu \sim a\text{ few GeV}$
Various types of atmospheric $\nu$ events (3)

- **97% CC $\nu_\mu$**

- **Upward going muon**
  - almost pure CC $\nu_\mu$

**Signal in the outer detector**

**Ev $\sim$10 GeV**

**Ev $\sim$100 GeV**

**Atmospheric Neutrino Oscillations**
Evidence for neutrino oscillations (Super-Kamiokande @Neutrino ’98)

Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.
Results from the other atmospheric neutrino experiments

These experiments observed atmospheric neutrinos and neutrino oscillations

↔ MINOS / SNO ↔
(Atmospheric neutrinos)
Data updates

Kamiokande (1994) → Super-K @Neutrino98 → Super-K @Neutrino 2012

No oscillation

Number of events plotted:

135 events

531 events

~4276 events

Atmospheric Neutrino Oscillations 28
$\nu_\mu \rightarrow \nu_\tau$ allowed parameter region

Super-K (1998)

Super-K (2012)

~1/10,000,000 of the electron mass

Y. Itow (SK nu2012)
Allowed parameter regions from present experiments

T2K collab. PRL 111, 211803 (2013)
Recent result and a remark on the future
Detecting CC $\nu_\tau$ events

If the oscillations are $\nu_\mu \rightarrow \nu_\tau$, we should observe $\nu_\tau$ interactions.

Example: $\nu_\tau$ event (MC)

We wanted to observe these events. The serious analysis started in ~2001.
Zenith angle distribution and fit results

Fitted number of $\tau$ events: $180.1 \pm 44.3\text{(stat)} +17.8/-15.2\text{(syst)}$

Expected number of $\tau$ events: $120.2+34.2/-34.8\text{(syst)}$

See also, SK PRL 97(2006)171801
Future

• Now we know the values of 3 mixing angles and 2 $\Delta m^2$’s based on results from various neutrino oscillation experiments.
• However, there are still unknowns of fundamental importance:

✓ Is the 3rd neutrino mass state really the heaviest (or the lightest)?
✓ What are the absolute neutrino masses?
✓ Are neutrinos and anti-neutrinos fundamentally the same particle?
✓ Are the oscillation of neutrinos and anti-neutrinos identical?
✓ And possibly much more...

➢ Atmospheric neutrinos, Long baseline neutrino oscillation experiments, ...
➢ KATRIN, ....
➢ Double beta experiments, ...
➢ Long baseline neutrino oscillation experiments, ...
➢ New idea (Your idea)!
Summary

• Unexpected muon-neutrino deficit in the atmospheric neutrino flux was observed in Kamiokande “accidentally” (1988).
• After that, Kamiokande and subsequently Super-Kamiokande tried to understand the cause of the deficit.
• I think it was lucky that Super-Kamiokande got a strong evidence for atmospheric neutrino oscillations in only 10 years (1998).
• I feel that I have been extremely lucky, because I have been involved in this discovery from the beginning.
• The discovery of non-zero neutrino masses opened a window to study physics at a very high energy scale, probably Grand Unification.
• There are still many things to be observed in neutrinos. Further studies of neutrinos might give us fundamental information for the understanding of the nature, such as the origin of the matter in the Universe.
Thank you very much for your attention!

Super-Kamiokande collaboration (End 1998)