Outline

• Kamiokande
• Super-Kamiokande
• Atmospheric neutrino oscillations
• Various oscillation studies
• Solar neutrino oscillations
• Future neutrino experiments in Kamioka
  • Appendix: Proton decay
• Summary
Kamiokande
In the 1970’s, Grand Unified Theories, predicted that protons should decay with the lifetime of about $10^{30}$ years.

Several proton decay experiments began in the early 1980’s.

One of then was the Kamiokande experiment.
Where is Kamioka?

(A photo taken some years ago. This year almost no snow.)

The original motivation was the search for proton decays.
 Didn’t observe proton decays, but...

No proton decay signal....

Pulse height distribution for electrons from the decays of cosmic ray muons (early autumn 1983)

Neutrinos with the energies of about 10 MeV could be observed.

✓ Improvement of the Kamiokande detector to observe solar neutrinos.
   (by M. Koshiba)
Results from Kamiokande

Detection of Supernova neutrinos (1987)

Observation of atmospheric neutrino deficit (1988)

Observation of solar neutrinos (1989)

Water Ch. is very important for neutrino phys. and astrophys.
Atmospheric neutrinos

Incoming cosmic rays

Cosmic ray
Air nucleus
Pion
Muon
Electron
2 muon-neutrinos
1 electron-neutrino
Atmospheric $\nu_\mu$ deficit (1988)

- In 1986, we wanted to improve the proton decay analysis. Therefore, several new software were developed. One of which was the particle identification (PID).
- As a test of new PID, the particle type for 1-ring atmospheric neutrino events was studied and realized the deficit of muon-neutrinos.

Many people (both experimentalists and theorists) thought that there must be something wrong in the analysis... (Mixing angle cannot be large.)
Neutrino oscillations (in the vacuum)

If neutrinos have masses, neutrinos change their type (flavor) from one type (flavor) to the other. For example, a muon-neutrino may oscillate to a tau-neutrino.

If neutrino mass is smaller, the oscillation length \((L/E)\) gets longer.

Theoretically predicted by:

S. Sakata, Z. Maki, M. Nakagawa

\(L\) is the neutrino flight length (km), \(E\) is the neutrino energy (GeV).
Super-Kamiokande
Super-Kamiokande detector

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

~20 times larger mass

~180 collaborators

1000m underground
In the fall of 1983, Prof. Koshiba recognized that solar neutrinos can be detected in Kamiokande. At the same time, he proposed Super-Kamiokande to study solar neutrinos in detail (and to search for proton decays).

Initial drawing of the Super-Kamiokande detector
(In “32 kton Water Cherenkov Detector (JACK) A proposal for detailed studies of nucleon decays and for low energy neutrino detection” by M. Koshiba, in Proceedings of workshop on Grand Unified Theories and Cosmology (Dec. 7-10, 1983, KEK, Tsukuba, Japan)
Super-Kamiokande construction (Summer 1995)
Filling water in Super-Kamiokande
Atmospheric neutrino oscillations
Fully automated analysis

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

**Multi Cherenkov ring event**

Hough transformation + maximum likelihood

![Graph showing Super Kamiokande data with ring counting likelihood sub-GeV(FC), stack.](image)
Event type and neutrino energy

All these events are used in the analysis.
What will happen if the $\nu_\mu$ deficit is due to neutrino oscillations

A deficit of upward going $\nu_\mu$'s should be observed! A large detector needed. ➔ Super-Kamiokande
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.

Y. Fukuda et al., PRL 81 (1998) 1562
Various oscillation studies
Updating atmospheric neutrino data

Super-K @ Neutrino 98

Super-K (2016)

Number of events plotted:

531 events  →  5932 events

Detailed studies of oscillations!
Detecting tau neutrinos

If the oscillations are between $\nu_\mu$ and $\nu_\tau$, one should be able to observe $\nu_\tau$'s.

A simulated $\nu_\tau$ event.

It is not possible for Super-K to identify $\nu_\tau$ events by an event by event bases. ➔ Statistical analysis knowing that $\nu_\tau$'s are upward-going only.

$\tau$-appearance at $4.6\sigma$ (consistent with OPERA)
Accelerator based long baseline neutrino oscillation experiments using Super-Kamiokande

**K2K experiment (1999 – 2004)**

Confirmation of neutrino oscillation ($\nu_\mu$ disappearance) with accelerator beam.

Electron neutrino appearance (evidence for 3 flavor oscillation effect).
**T2K (L. Pickering, NNN2019)**

*Prediction ‘1σ’ uncertainties at best fit*

**NOvA (E. C. Mur, NNN2019)**

**NOvA Preliminary**

- **NOvA FD**
  - $\sin^2 \theta_{13} = 0.082$
  - $\Delta m^2_{32} = -2.54 \times 10^{-3} \text{eV}^2$
- **UO**
  - $\sin^2 \theta_{23} = 0.56$
  - $\Delta m^2_{32} = +2.48 \times 10^{-3} \text{eV}^2$

**Total events - antineutrino beam**

- $\delta_{\text{CP}} = 0$ (LO), $\delta_{\text{CP}} = \pi/2$ (IH)
- $\delta_{\text{CP}} = \pi$ (NH), $\delta_{\text{CP}} = 3\pi/2$ (2019 best fit)
Constraints on the CP phase (based on NNN 2019, Nov. 2019)

**Super-K atmospheric (L. Wan)**

- Normal Hierarchy
- Inverted Hierarchy

**T2K (L. Pickering)**

- NO favored by these 3 experiments at ~ (1 ~ 2) sigma level each.
- These experiments give some favored $\delta_{CP}$ region(s).

**NOvA (E. C. Mur)**

- NO favored by these 3 experiments at ~ (1 ~ 2) sigma level each.
- These experiments give some favored $\delta_{CP}$ region(s).

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**Legend**

- $\Delta \chi^2$
- $\sin^2(\theta_{23})$
- $\delta_{CP}$

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**Graphical Representation**

- NO: Normal Hierarchy
- IO: Inverted Hierarchy

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**ArXiv:1910.03887**

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**NOvA Preliminary**
Global fit (example)

I. Esteban et al., JHEP 1901 (2019) 106

- NO favored.
- Suggested $\delta_{CP}$ range(s)

(w/o SK atm)  (with SK atm)
Solar neutrino oscillations
In the 20th century, several experiments observed solar neutrinos.

These solar neutrino experiments observed the deficit of solar neutrinos.

SNO $\nu_e$ flux

Super-K ES $(\nu_e + \nu_\mu + \nu_\tau$ flux)

SNO $\nu_e + \nu_\mu + \nu_\tau$ flux

$\nu_e D \rightarrow e^- pp$

$\nu_\mu + \nu_\tau$ flux!!

$\nu_e \rightarrow \nu_\tau$

Neutrino oscillation: electron neutrinos to the other neutrinos.

1000 ton of heavy water ($D_2O$)

SK, PRL 86 (2001) 5651
SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)
KamLAND (another experiment in Kamioka)

KamLAND is a 1kton liquid scintillator exp. constructed at the location of Kamiokande.

Many nuclear power stations around KamLAND at the distance of about 180 km. ➔ Long baseline reactor neutrino osc. experiment.
Really neutrino oscillations!

Energy spectrum of neutrinos from nuclear power stations observed in KamLAND.

OR
Status of the 12-parameter measurements

\[ \Delta m^2_{21} \text{ in } 10^{-5} \text{ eV}^2 \]

\[ \sin^2(\theta_{12}) \]

Filled regions: 3\(\sigma\)

S. Moriyama (Super-K), Neutrino 2016

KamLAND
SK+SNO+KamLAND
SK+SNO

\( \sim 2\sigma \) tension
Further studies of solar neutrino osci. with Super-K

**Day-Night effect**

\[
A_{DN} = \frac{(\text{Day} - \text{Night})}{(\text{Day} + \text{Night}) / 2}
\]

**Spectrum upturn**

<table>
<thead>
<tr>
<th>( A_{DN} ) fit (%)</th>
<th>SK-I~IV, 4499 days</th>
<th>-3.3(^\pm)1.0(^\pm)0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-zero significance</strong></td>
<td>2.9 ( \sigma )</td>
<td></td>
</tr>
</tbody>
</table>

-1\%  
-2\%  
-3\%  
-4\%  

Interesting. But we need more data.

(Super-K, Neutrino 2018)

**Solar+KamLAND best fit**  
**Solar global best fit**

- Consistent within 1.5\( \sigma \)
- Marginally within ~2\( \sigma \)
Future neutrino experiments in Kamioka
Agenda for the future neutrino measurements

**Neutrino mass ordering?**

- Normal
- Inverted

**Absolute neutrino mass?**

**Beyond the 3 flavor framework?**

(Sterile neutrinos?)

**CP violation?**

$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu_\alpha} \rightarrow \bar{\nu_\beta})$?

Baryon asymmetry of the Universe?

**Are neutrinos Majorana particles?**

⇒ Neutrinoless double beta decay

http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html
We would like to confirm that CP is violated in the neutrino sector.

CP violation in the neutrino sector might be the key to understand the baryon asymmetry of the Universe (Leptogenesis).

...
Present experiments give some interesting hints…
We need the next generation experiments to clearly observe the CP violation in the neutrino sector.
Hyper-K as a natural extension of water Ch. detectors

**Kamiokande & IMB**
- Neutrinos from SN1987A
- Atmospheric neutrino deficit
- Solar neutrino (Kam)

**Super-K**
- Atmospheric neutrino oscillation
- Solar neutrino oscillation with SNO
- Far detector for K2K and T2K

**Hyper-K**

**KEK-PS**

25 collaborators from Russia in T2K
Hyper-K detector will be used to study:

- Neutrino oscillations with J-PARC neutrino beam (1.3MW beam),
- atmospheric neutrino oscillations,
- solar neutrino oscillations
- Proton decays
- Supernova neutrino burst
- Past supernova neutrinos
- ....

Φ 68 meters and H 72 meters.
The total and fiducial volumes are 0.26 and 0.19 M tons, respectively.

Hyper-Kamiokande proto-collaboration,
~340 members from 17 countries.

New members are most welcome!
Hyper-K location

- ~8km south of Super-K.
- 295km from J-PARC and 2.5 deg. Off axis beam
- 650 m rock overburden

A result from a finite element analysis on cavity stability.
⇒ OK with support structure.
Hyper-K with J-PARC neutrino beam

22.5 kton (Super-K) to 19 Mton (Hyper-K) = x 8.4

500 kW beam in 2019 to 1.3 MW beam in ~2028 = x 2.6

x ~22 higher neutrino event rate than T2K
**Sensitivities**

**DUNE**

(E. Worcester, nu2018)

![DUNE Sensitivity Graph](chart)

**Hyper-K**

(M. Shiozawa, nu2018)

![Hyper-K Sensitivity Graph](chart)
### Complementarity

<table>
<thead>
<tr>
<th>DUNE</th>
<th>Hyper-K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>1300km ➔ Large matter effect</td>
</tr>
<tr>
<td></td>
<td>(Good for Mass Ordering determination)</td>
</tr>
<tr>
<td>Beam energy</td>
<td>~ Multi-GeV</td>
</tr>
<tr>
<td>Detector technology</td>
<td>Liq. Ar TPC</td>
</tr>
</tbody>
</table>

- **We would like to be convinced the CP violation by the consistent results from these 2 experiments with very different systematics.**
- **We hope that these 2 experiments will carry out the measurements in a similar timeline.**
After the initial CP results...

DUNE (E. Worcester, nu2018)  

Hyper-K (M. Shiozawa, nu2018)

If the suggested CP phase by T2K and Super-K (around $3/2\pi$ or $-\pi/2$) is close to the real value, the determination of the CP phase angle will be rather poor.

➤ Should we better measure the phase angle? We would like to get inputs from theorists.
Other oscillation studies
Solar neutrino oscillations

Status of the 12-parameter measurements

S. Moriyama (Super-K), Neutrino 2016

~2σ tension
Day-night effect is one of the keys;  
- to understand $\Delta m_{12}^2$  
- to confirm the standard matter effect
Appendix: Proton decay
Motivation

✓ It is clear that proton decay is very important for understanding of physics at the very high energy scale (GUTs).
✓ Neutrino masses/mixings and proton decays might be related to the physics at very high energy scale.
✓ We are in an extremely interesting era. New large neutrino detectors (JUNO, DUNE and Hyper-K) will begin the operation in the near future. These detectors are also very good proton decay detectors.
✓ Therefore, we should not forget the proton decay searches with the next generation “neutrino oscillation experiments”.
Proton decay sensitivities

Hyper-K 3σ detection potential (20 years):
$\tau_p < 10^{35}$ years ($e\pi^0$) or $< 3 \times 10^{34}$ years ($\nu K^+$)

(Lines for DUNE and JUNO experiment have been generated based on numbers in the literature.)
In order to reach $10^{35}$ years, “free” proton decay (from Hydrogen) is very important!
Key plots for confirming $p \rightarrow e^+ \pi^0$

$p \rightarrow e^+ \pi^0$ Invariant Mass

$\tau_{\text{proton}}=1.7 \times 10^{34}$ years (SK limit)

(Hyper-K, arXiv:1805.04163v1)
In 2017, Hyper-K was selected as one of the 7 large scientific projects in the Roadmap of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT).

In Japanese FY 2019, Hyper-K received the “seed funding” to prepare for the construction.

On Dec. 13, 2019, the Japanese Cabinet has proposed the supplementary budget for FY2019. It includes the budget for the construction of Hyper-K.

On Dec. 20, 2019, the Japanese Cabinet has proposed the regular budget for JFY 2020. It also includes the budget for the construction of Hyper-K.

On January 30, 2020 (TODAY), the supplementary budget for JFY 2019 was approved by the Japanese Diet!

Hyper-K construction starts NOW!
You are most welcome to work together in Hyper-K!
Timeline

Today

Geo. Survey

Kamioka

J-PARC

Access, Cavity design

PMT production

PMT cases, Mirrors, Electromics etc.

Power-upgrade of J-PARC and Neutrino Beam-line

Near Detector Facility, R&D, production

Cavity excavation

Tank Const.

Water system

PMT installation

Filling water

Operation

FY2020 FY2021 FY2022 FY2023 FY2024 FY2025 FY2026 FY2027 FY2028
Summary

• Experiments in Kamioka have been contributing to neutrino physics:
  • Kamiokande observed supernova neutrinos and the atmospheric neutrino deficit, and confirmed the solar neutrino deficit.
  • Super-Kamiokande discovered neutrino oscillations, and contributed to the solar neutrino oscillation and to the LBL neutrino oscillation experiments.
  • KamLAND observed reactor neutrino oscillations and geo-neutrinos.

• We would like to continue contributing to neutrino physics with the next generation experiment, Hyper-K.

We would like to work together with the Spanish and International colleagues in the Hyper-K project.