Lecture: Super-Kamiokande

2019/07/10

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Contents

1. Why was SK born?
2. History about SK
3. Studies at SK
4. Key technology
1. Why was SK born?

- The Standard Model is very beautiful and successful to explain high energy phenomena.
- But there are so many parameters which can not explain by the standard model itself.
- Is it really fundamental theory?

So many actors in the Standard Model theater....
• Strength of three interactions seems to meet at very high energy.
• Grand Unified Theory (GUTs) was proposed to unify three forces.
• If it is true, leptons and quarks could transform each other.
• Proton could be decayed!
• I will have a lecture about proton decay on Thursday in the next week. Stay tuned!
• In the late 1970s, several experiments were proposed for discovery of proton decay.
  - minimal SU(5) prediction: $10^{28} \sim 10^{32}$ years
  - Age of universe: $\sim 1.3 \times 10^{10}$ years
  - It is impossible to continue observation one proton for such long time, but it is equivalent to study large number of proton in short time.
  - 1kt detector expected $10 \sim 10^3$ decays/year.

• Like gold rash, many large detectors were build.

• Two types of detector came into fashion (the 1st generation).

  **Fine-grained iron calorimeter**
  - Excellent in track reconstruction.
  - Cost per ton were expensive.
  - KGF (India), Soudan I,II (Minnesota), NUSEX (Italy/France)

  **Water Cherenkov detector**
  - Good momentum resolution and PID.
  - Cheaper and easier to build larger detectors.
  - HPW (Harvard-Purdue-Wisconsin), IMB (Irvine, Michigan, Brookhaven), Kamiokande
### Results of Water Cherenkov detector

<table>
<thead>
<tr>
<th>Detector</th>
<th>Period</th>
<th>Mass (ton)</th>
<th>Limit ((e^+\pi^0, 10^{30}\text{ yr}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPW-I</td>
<td>1983-1984</td>
<td>680</td>
<td>1.0</td>
</tr>
<tr>
<td>Kamioka</td>
<td>1983-1997</td>
<td>1040</td>
<td>260</td>
</tr>
<tr>
<td>IMB</td>
<td>1982-1992</td>
<td>3300</td>
<td>540</td>
</tr>
</tbody>
</table>

### Results of Iron calorimeter

<table>
<thead>
<tr>
<th>Detector</th>
<th>Period</th>
<th>Mass (ton)</th>
<th>Limit ((e^+\pi^0, 10^{30}\text{ yr}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUSEX</td>
<td>1982-1998</td>
<td>110-130</td>
<td>15</td>
</tr>
<tr>
<td>Frejus</td>
<td>1984-1988</td>
<td>550</td>
<td>70</td>
</tr>
<tr>
<td>Soudan I</td>
<td>1981-1990</td>
<td>16-24</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Could not find evidence. Need more volume!
• By the way, background events for proton decay are induced events by neutrino.
• Need to study neutrino (finally, they became famous as neutrino detector rather than proton decay detector).
• There were unexpected results on neutrino.
  ➢ Solar neutrino problem
  ➢ Atmospheric neutrino problem
• Observed Super Nova neutrino in 1987.
• To investigate in detail, also larger detector was needed.
• Kamikande and IMB group collaborated to build Super-Kamiokande.
Location: Kamioka mine, Japan. ~1000 m under ground.
Size: 39 m (diameter) x 42 m (height), 50kton water.
Optically separated into inner detector (ID) and outer detector (OD, ~2.5 m layer from tank wall.)
Photo device: 20 inch PMT (ID), 8 inch PMT (OD, veto cosmic rays, ~1/3 comes from IMB).
Mom. resolution: 3.0 % for e 1 GeV/c (4.1%: SK-2).
Particle ID: Separate into EM shower type (e-like) and muon type (μ-like) by Cherenkov ring angle and ring pattern.

μ-like (μ±)  e-like (e ±, γ)
Where is Super-Kamiokande?

- Super-Kamiokande locates under ground of Ikenoyama mountain, Kamioka, Gifu, in Japan.

In winter, we have much snow.
Underground laboratories
Super-Kamiokande collaboration

- Host: Institute for Cosmic Ray Research (ICRR), University of Tokyo
- **10 countries**: Japan, US, Canada, China, Korea, Poland, Spain, UK, Italy, France
- ~170 members
Amazingly, SK still runs stably more than 20 years.
Evidence of neutrino oscillation

Slide in Neutrino 1998

Win Nobel prize in 2015
2001 Implosion accident

Barrel

Bottom

About a half of PMT (~6000) were broken ....
What happened?

- Inside of photomultiplier tube (PMT) is vacuum.
- One of PMT in the bottom was crashed (unknown cause).
- Water came into inside and made big shockwave due to high water pressure.
- The shockwave destroyed neighbor PMTs.
- The chain reaction destroyed many PMTs.
It was miracle that we reconstructed SK with remaining 5182 ID PMTs just in one year.

Our boss, Totsuka said “There is no question. We will reconstruct SK!".

Acrylic (front) + FRP (back)
3. Studies in SK: Atmospheric $\nu$

Primary cosmic ray
$p, \text{He}, \ldots$

$\pi^{\pm}, K^{\pm}$

Large background. To prevent muon, SK's located underground.
Solar ν

4H $\rightarrow$ $^4$He + 2e$^+$ + 2ν$_e$

Large number of neutrino: ~6x10$^{10}$ ν$_e$/sec/cm$^2$

Good information to know what is going on inside of the solar.
Super Nova ν

Neutrinos carry ~99% of energy at Super Nova. They give us information on how SN happens.
Proton decay

- It is a key to **beyond Standard Model**.
- $p \rightarrow e^+\pi^0$ and $p \rightarrow \nu K^+$ are dominant modes.
- It may bring the 3rd Nobel prize to Kamioka.
- More details will be given on Thursday in the next week.
Shot $\nu$ made by accelerator to SK at 295km far away to investigate neutrino oscillation precisely.
Opening new era! : SK-Gd

- Current SK: Ultra-pure water
- Quasi-elastic scattering:
  \[ \nu_e \, n \rightarrow e^- \, p \]
  \[ \bar{\nu}_e \, p \rightarrow e^+ \, n \]
- SK can’t identify charge.
- But if we put Gd into water, we can separate neutrino and anti-neutrino reaction by 8 MeV γ from neutron capture of Gd.
  ➔ SK-Gd project
• Benefit of SK-Gd
  ➢ Increase sensitivity for super nova neutrino
  ➢ Better sensitivity CP violation in neutrino oscillation
  ➢ Reduction background events for proton decay.
  ➢ And so on.

• Before Gd loading, we have to stop water leak.
  ➢ Leak rate: ~ 1ton/day = 700ml/min, not so much.
  ➢ Wastewater from Kamioka mine which include cadmium (Cd) flowed into river and it caused “Itai-itai disease” until 1970’s.
  ➢ How Gd affects on human health has not been reported, and we will use 0.2 % Gd concentration.
  ➢ However, local people are very sensitive to this kind of problem.
  ➢ We decided to open SK tank to fix water leak, and also replace bad PMTs since this June.
Super-Kamiokande in the last year
Outer wall of SK tank

SK tank wall is made of stainless steel plates (2m x 8m) connecting by welding each other.

We assume water leaks from welding part and decided to seal all welding lines.
In this chance, we are replacing bad PMTs (~130). PMT replacement 1: prepare PMT module

Cleaning PMT and check glass surface.  
Attach PMT cover.
PMT replacement 2: Attach to tank

Working on floating floor

Removing bad PMT

Attach new PMT
• ~30 researchers worked for this work everyday
• The work continued until middle of September, 2018.
• Start to fill water from October, and finished filling in this January.
• We confirm water leak has been stopped!
• After many calibration works in February and March, we resumed data taking with pure water.
• Gd loading is planned in the next February.
4. Key technology

How neutrino can be detected in SK?

- Neutrino is light and neutral particle. **Neutrino itself can not be seen**, but it rarely interacts with nucleon or electron. Ex. $\nu_e n \rightarrow e^- p$.

- **Kicked out charged particle emits Cherenkov light** in water.

- Cherenkov light propagates in water and it is detected by PMT.

- From amount of light and arrival time, vertex, direction, particle type and momentum of charged particle can be obtained.

- From those information, **we can obtain information of neutrino**.
$\nu_e$: Invisible

$e^-$: Charged particle

Oxygen

Cherenkov light

Photo sensors
• So, roughly say, SK is made of:
  ➢ Tank
  ➢ Water
  ➢ Photo detector (PMT)
  ➢ Readout electronics
5-0. Cherenkov light.

- Cherenkov light emission: Electromagnetic phenomena.
  - Similar to sonic boom.
- It happens a charged particle moves faster ($\beta$) than light velocity in the medium, $c/n$.
  - $c$: velocity of light in vacuum,
  - $n$: reflective index of the medium

$$\cos \theta_c = \frac{1}{n\beta}$$
\[ \cos \theta_c = \frac{1}{n \beta} \]

- Water: \( n=1.34, \beta \sim 1 \) \( \Rightarrow \theta_c \sim 42^\circ \)

\[ \beta \geq \frac{1}{n} \]

- The condition to emit Cherenkov light (Cherenkov threshold) for electron: > 0.57 MeV/c

(Excise)
Calculate Cherenkov threshold for muon (\( m_\mu =106 \text{ MeV/c}^2 \)) and pion (\( m_\pi =140 \text{ MeV/c}^2 \)).

Hint: \( p=m\beta\gamma = m\beta/\sqrt{1-\beta^2} \)

NOTE: Heavier particle has smaller \( \theta_c \) with same momentum.
\( \Rightarrow \) Used in particle identification.
5-1. Tank

- Located ~1000 m below mountain peak. The mountain acts as filter for cosmic muons

Contain 50 k ton water!
Even 1000 m underground, cosmic ray muons reach to SK (~several tenth Hz).

SK is optically divided into two layer (inner and outer).

PMTs are attached on inner wall.

20 inch PMTs are facing inward and 8 inch PMTs are outward.

Cosmic ray muon can be rejected because it produces photons in outer layer.

On the other hand, $\nu$ which interacts inner doesn’t have photon in outer layer.
5-2. Water system

- SK is filled by 50 kton ultra pure water.
  - The source is spring water in the mine which contains radio active materials (dominant: Radon). They are tremendous background in low energy region.
  - Cherenkov light is affected by absorption and scattering in water. Light is decreased as:
    \[ I = I_0 \exp\left(-\frac{x}{L_{Atn}}\right) \]
    where \( L_{Atn} \) is attenuation length (~100 m at SK).
  - Water is circulated all the time, filled from the bottom and drain at the top. To prevent convection and bacteria, filling water temperature should be well controlled at 13.06 degree.
Temperature control is important for water quality

\[ T_{in} > T_{tank}: \text{Convection happens.} \]
\[ \rightarrow \text{Dust in bottom is stirred up.} \]
\[ \rightarrow \text{Worse water quality.} \]

\[ T_{in} < T_{tank}: \text{Laminar and water raised up quietly.} \]
\[ \rightarrow \text{Better water quality} \]
Super-K "water" system
5-3. Photomultiplier tube (PMT)

- **Photo cathode**: Glass covered by biarkari and a photon is converted to electron (so called photoelectron) with ~20 % efficiency (quantum efficiency or QE).

- Between anode and cathode, ~2000 V HV is applied. Photoelectrons are accelerated and hit first dynode and produce secondary electrons. There are several dynodes and repeat the process to achieve high gain (~$10^7$).
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shape</strong></td>
<td>Hemispherical</td>
</tr>
<tr>
<td><strong>Photocathode area</strong></td>
<td>50 cm diameter</td>
</tr>
<tr>
<td><strong>Window material</strong></td>
<td>Pyrex glass (4 ~ 5 mm)</td>
</tr>
<tr>
<td><strong>Photocathode material</strong></td>
<td>Bialkali (Sb-K-Cs)</td>
</tr>
<tr>
<td><strong>Quantum efficiency</strong></td>
<td>22% at $\lambda = 390$ nm</td>
</tr>
<tr>
<td><strong>Dynodes</strong></td>
<td>11 stage Venetian blind type</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>$10^7$ at $\sim 2000$ V</td>
</tr>
<tr>
<td><strong>Dark current</strong></td>
<td>200 nA at $10^7$ gain</td>
</tr>
<tr>
<td><strong>Dark pulse rate</strong></td>
<td>3 kHz at $10^7$ gain</td>
</tr>
<tr>
<td><strong>Cathode non-uniformity</strong></td>
<td>$&lt; 10%$</td>
</tr>
<tr>
<td><strong>Anode non-uniformity</strong></td>
<td>$&lt; 40%$</td>
</tr>
<tr>
<td><strong>Transit time</strong></td>
<td>90 nsec at $10^7$ gain</td>
</tr>
<tr>
<td><strong>Transit time spread</strong></td>
<td>2.2 nsec (1$\sigma$) for 1 p.e. equivalent signals</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>13 kg</td>
</tr>
<tr>
<td><strong>Pressure tolerance</strong></td>
<td>6 kg/cm$^2$ water proof</td>
</tr>
</tbody>
</table>

Table 2.1: Specifications of 20-inch PMT.
Reduce light due to scattering

Reduce light due to absorption.

Spectrum of Cherenkov light and QE

Quantum Efficiency of SK PMT is optimized to detect Cherenkov light
Typical response for one photon

Miss some dynodes, \( \sim 30 \% \)
Correctly multiplied.

Figure 2.7: Single photoelectron distribution of a typical 20-inch PMT.

Photon \( \rightarrow \) Charge pulse
5-4. Electronics and readout

Figure 3.10: The schematic view of the DAQ system used in SK-IV [97].
Width corresponding to integrated Q in 400ns

Time:

Threshold: 0.69 mV

Make digitized T and Q for each PMT

Send to Front PC via ethernet
• Front-end PC
  - Sort PMT data by time. Send to Merger PC.

• Merger PC: apply software trigger
  - Count number of hits in 200 ns ($N_{200}$). If it exceed threshold, make trigger
  - Define a event as hit cluster with time window for each time window. Events are save in disks.

Table 3.6: The threshold for each trigger and its event time width.

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>Threshold for $N_{200}$ [hit PMTs]</th>
<th>Event timing width [$\mu$s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLE</td>
<td>34 → 31 (After May 2015)</td>
<td>1.5 ($-0.5 \sim +1.0$)</td>
</tr>
<tr>
<td>LE</td>
<td>47</td>
<td>40 ($-5 \sim +35$)</td>
</tr>
<tr>
<td>HE</td>
<td>50</td>
<td>40 ($-5 \sim +35$)</td>
</tr>
<tr>
<td>SHE</td>
<td>70 → 58 (After September 2011)</td>
<td>40 ($-5 \sim +35$)</td>
</tr>
<tr>
<td>OD</td>
<td>22 in OD</td>
<td>40 ($-5 \sim +35$)</td>
</tr>
</tbody>
</table>
6. Introduction of software training: Particle Identification (PID)

- Electron/ gamma case
  - It makes electromagnetic shower and make many $e^-$ and $e^+$.
  - Each of them makes Cherenkov light.
  - Thus, ring pattern becomes defused.
- Muon/ pion case
  - Doesn’t make electromagnetic shower.
  - Ring edge becomes rather sharp.
  - In smaller momentum, Cherenkov angle becomes less than 42° because of low $\beta$. 
Can you identify electron and muon by your eyes?
To be continued to software training......
Appendix
Answer of page 33

muon $\sim 119$ MeV/c, charged pion $\sim 157$ MeV/c

$$P_{th} = \frac{m\beta^2}{\sqrt{1-\beta^2}} = \frac{m}{\sqrt{n^2-1}}$$