Research Internship at Okayama University, Japan

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I would also like to extend my thanks to all the Japanese students I worked with during my internship. Their hospitality and assistance gave me the confidence to achieve my objectives. Their help and explanations were essential to the success of my tasks.

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Introduction

Currently in my second year at Grenoble INP Phelma (**Ph**ysics, **El**ectronics, and **Ma**terials) in Master's Degree in Engineering, Reactor physics and nuclear engineering specialty (GEN). Throughout my master's degree, I have acquired a solid understanding of Physics fundamentals, especially in Nuclear Physics and Matter-Radiation Interactions and Detectors. Furthermore,this knowledge is complemented by a robust understanding of Numerical Methods.

I developed a sincere intereste regarding Neutronics and Particle Physics in general. I expected to explore scientific research in a group during my first year of master's of engineering. Therefore working at Okayama University with Dr. Koshio was a great opportunity to apply my knowledge in particle detection learned at Grenoble INP Phelma. His group works on the simulation and the analysis of Super-Kamiokande's data, "a research experiment that aims to unravel the mysteries of elementary particles and the universe through observations of neutrinos"[4].

My internship at Okayama University, Graduate School of Environmental, Life, Natural Science and Technology is a data analysis project over **High Energy Physics - Supernova Neutrino detection in Super-Kamiokande**. This report will synthesize my experience focusing firstly on the scientific stakes of Super-Kamiokande and especially neutrino detection. Then, we will review the scientific record of my work and finally consider the challenges and opportunity of this mobility in Japan.

1 Super-Kamiokande

1.1 The Super-Kamiokande project [2]

The Super-Kamiokande, also known as SuperK or SK, is a Cerenkov detector located under mount Ikeno, Gifu Prefecture, for the time being it is the largest in the world (see Hyper-Kamiokande [3]). It consists in a 40m diameter and 40m height stainless steel cylinder filled with extremely pure water, with about 13 000 PMTs (Photo-multiplier Tubes) on its inner wall and surface. Charged particles going faster than light in water emits a ring of Cerenkov light which is detected by the different PMTs. Considering the energy and the shape of these rings, it is possible to infer the interaction and the original incident particle: a neutrino, its energy and its flavor for example.

1.1.1 History of Super-Kamiokande [1]

The Super-Kamiokande is the succession of the Kamiokande which was a smaller version of this detector. The Kamiokande started in 1983 and permitted to detect the supernova neutrinos from the supernova SN1987A in the Large Magellanic Cloud, about 49pc away. In 1988, solar neutrinos were detected for the first time. The success of Kamiokande led to the construction of SuperK that started on April 1, 1996. Its better precision compared to its previous version permitted the discovery of neutrino oscillation and consequently the mass of the neutrino (2015 Nobel Prize in Physics, Takaaki Kajita [4])

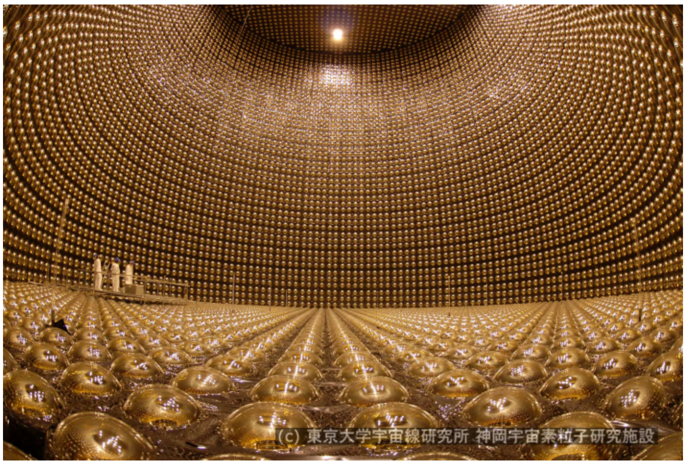

Figure 1: Interior of SuperK nearly full of PMTs

In 2027, the SuperK will make way for its better version: the Hyper-Kamiokande, 68m diameter x 71m height, 260000 ton of ultra pure water.

1.1.2 Purpose of SuperK

The Super-Kamiokande is a multi-purpose project : discover the properties of neutrinos through solar and atmospheric neutrino flux, T2K experiment ; understand the physics of supernovae (local burst neutrinos, diffuse supernova neutrino

background) ; searching for proton decay and dark matter interactions.
Therefore, Kamiokande, SuperK and HyperK participate in the elucidation of the origin of the universe.

1.1.3 The challenges of SuperK today

The work of researchers of this project is maintenance, improvements, data collection and finally data analysis. As a gigantic experiment, it is in constant evolution through the years to improve the detection and the results. The different phases of SuperK resolved issues such as an accident in November 2001 that destroyed about half of the PMTs, SK-II operated with roughly half the number of PMTs. In July 2020, the detector was loaded with gadolinium sulfate to enhance its ability to detect neutrons. In fact, the detection of antineutrinos results from inverse beta decay, and emits a positron and a neutron which is capture by gadolinium emitting gamma rays.

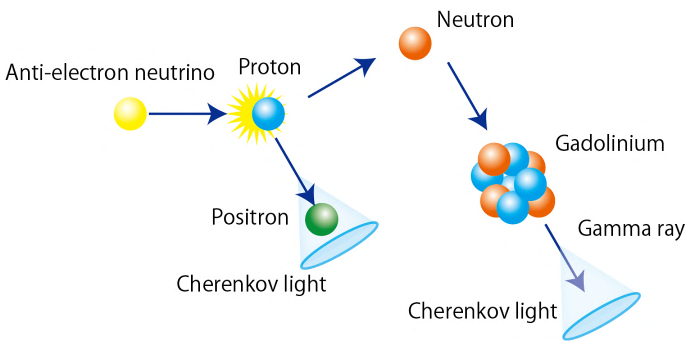

Figure 2: Inverse beta decay and neutron capture on Gd [5]

The most recent event is the rupture of the fifth magnetic coil. These coils help to create a magnetic field within the tank, which can influence the direction and trajectory of charged particles produced in neutrino interactions. The goal is to compensate the geomagnetic field to enhance the quantum efficiency of the PMTs. The rupture of one coil modified the efficiency of each PMT as the geomagnetic field is partially blocked. All the data that has been collected since then needs new calibrations and simulations to be understand. The group I joined is working on Monte Carlo simulations to establish the quantum efficiency and calibration events tables.

1.2 Contributions and achievements

The Super-Kamiokande has become globally famous since 1998 providing first clues that neutrino can oscillate between lepton flavors (electron, muon, tau). This proof would ensure that neutrino have mass.

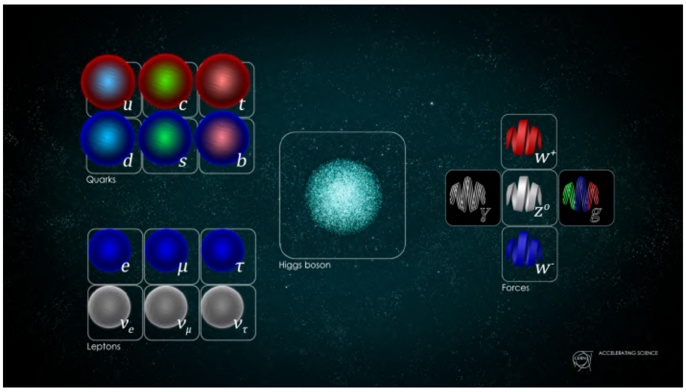

Figure 3: Standard Model [6]

2002 Nobel Prize : Awarded to Raymond Davis Jr. and Masatoshi Koshiba for detection of neutrino from the Sun and cosmic sources, offering direct evidence of solar neutrinos and validating the theorical models of stellar processes

In 2011, the T2K experiment (an artificial neutrino beam in Tokai, Japan, aiming at the SuperK) observed for the first time an oscillation from muon neutrino to electron neutrino.

2015 Nobel Prize : Takaaki Kajita and Arthur B. McDonald. **Discovery of Neutrino Oscillations**. This discovery was a fundamental breakthrough challenging the standard model and demonstrating that neutrino have a mass, which was previously thought to be zero. This finding has deep implications for our understanding of the universe and the fundamental properties of particles.

2 Scientific Report

2.1 Introduction

One of the major challenge of the SuperK is to be as efficient as possible, which means being able to detect events even with a few number of entries, with a large range of energy. The former depends on the reduction, or the interpretation of each component of the background. For example, significant part of this background is due for example to the nuclear power reactor neutrino flux. In fact, the 235U nuclear fission produces approximately 6 antineutrino, therefore the surrounding nuclear plant around mount Ikeno.

The source of background that we will focus on in this project is the neutron flux due to muon spallation

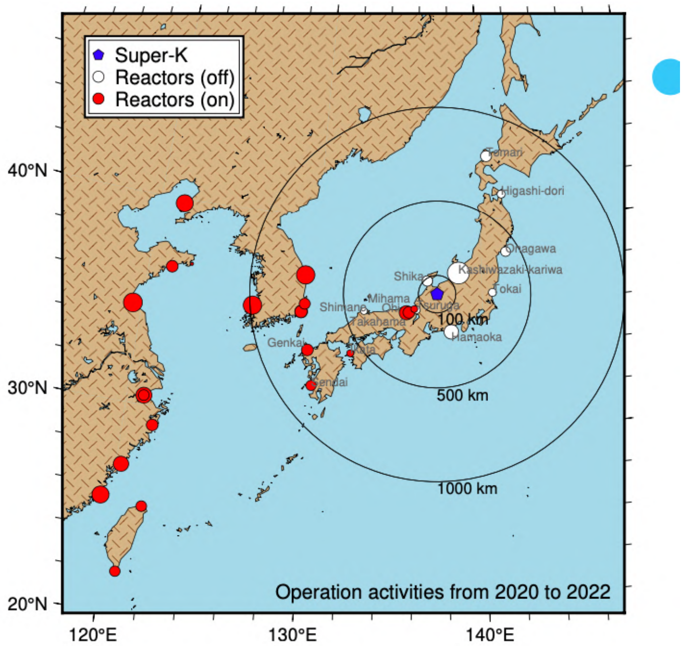

Figure 4: Surrounding nuclear plants [7]

Even if we try to understand every part of this background, we are not able to explain the SuperK noise perfectly. In fact there is a peak around 5MeV that is not yet clarified. One hypothesis is the spallation of high energy muons which emits neutrons near the tank of the SuperK. These are detected through capture on Gd or H emitting gamma rays Cerenkov light.

2.2 Theoretical background and Experiments

The goal of my study is to estimate the influence of muons in the Super Kamiokande background noise. To achieve this we first need a simulation recreating muon spallation events. This simulation is programmed on SKG4 (A SK adaptation of Geant4). This simulation was coded by Hino-san, a post-doctorate SK collaborator working in Koshio Sensei's laboratory.

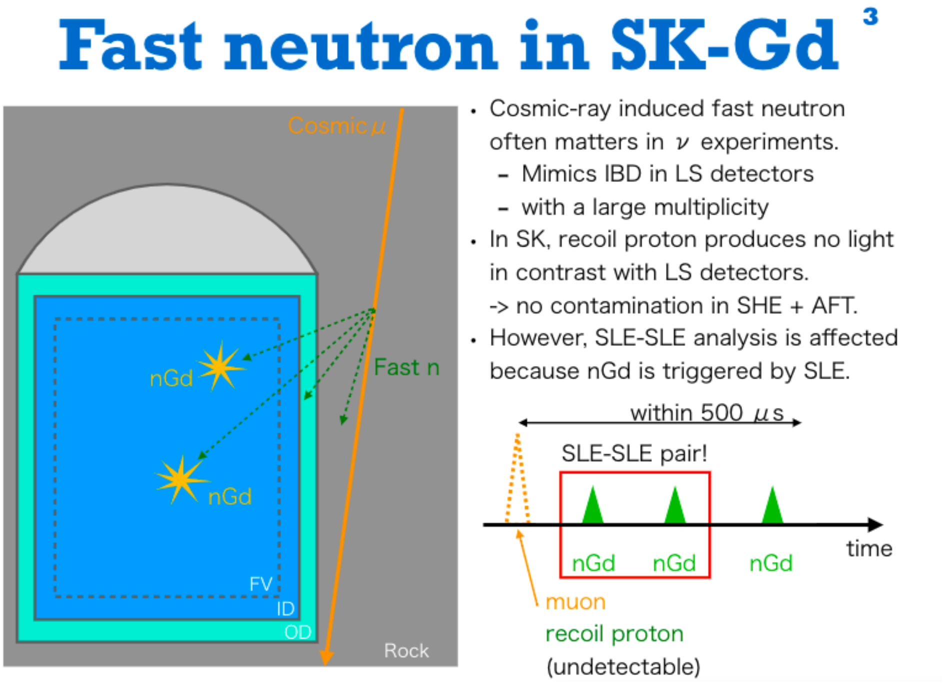

Figure 5: Izumiyama-san's explanations [13]

The first objective is to run the simulation properly, then we need to accumulate simulations to create a great number of event to improve statistics of the analysis. The next step is the data analysis. In fact we need to discriminate the events to keep only the ones that will participate in the background. In fact, will take part in the background the events which can be confused with an inverse beta decay (IBD). We use different parameters of the events to create cut criteria, actually IBD can be recognizable with the distance and time between prompt and delayed Cerenkov emission, energy, Cerenkov angle, distance from the walls of the SuperK.

Here's a brief explanation of the parameters related to Super-Kamiokande:
Prompt energy: The energy deposited by the initial interaction of a neutrino in the detector.
Delayed energy: The energy detected after the prompt signal, often from secondary processes like neutron capture.
Delta t: The time difference between the prompt and delayed signals.
Delta VTX: The spatial distance between the vertices of the prompt and delayed events.
dWall: The distance from the event vertex to the nearest detector wall.
Angle: The angle between the prompt and delayed event directions.
MSG (Multi-Scatter Gamma): A flag indicating potential gamma-ray scattering events.
PiLike: A parameter used to identify pion-like particle events.
q50/n50: Ratio indicating the event's charge distribution over 50 percents of the photo-multiplier tubes. [11] [12]

2.3 Results and analysis

The first goal was to initiate the simmulation and see if the root analysis worked. Here every green dots represents every gamma Cerenkov emission that occurs in the detector.

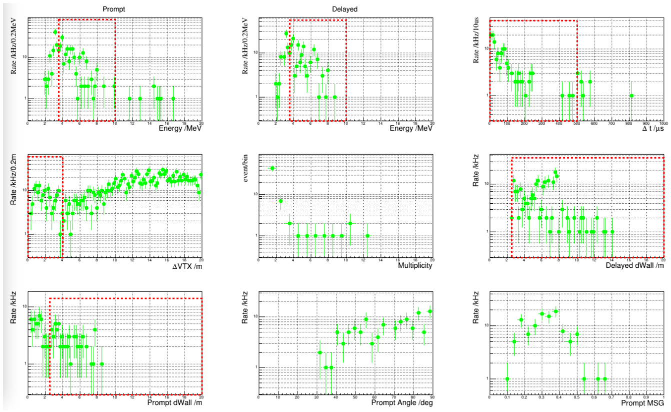

Figure 6: Results of 10 simulations of 10,000 events (Before cut) [8]

Then, the cut analysis permit to reduce the events on the graph to IBD-like (inverted beta decay) events. That means these plots show the details of the IBD like event due to muon spallation from a rain of 10,000 muons

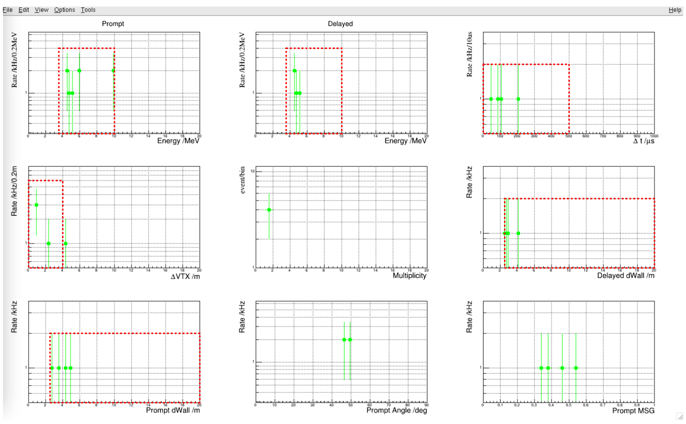

Figure 7: Results of 10 simulations of 10,000 events (After cut) [9]

Here are the results and conclusion of my work after multiplying statistics.

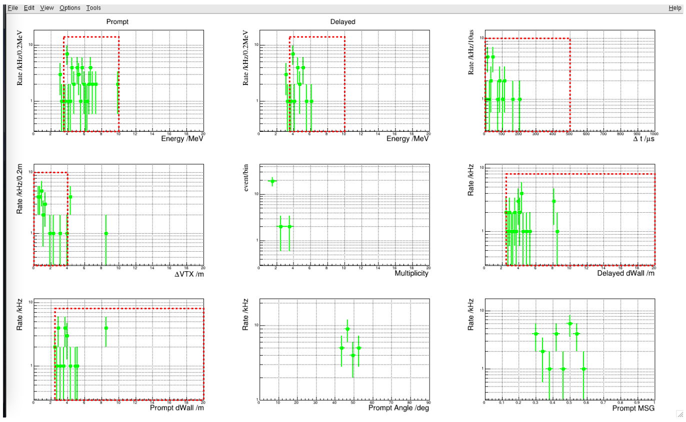

Figure 8: Results of 100 simulations of 10,000 events (After cut) [10]

Finally, the most interesting result is the number of event remaining leading to the event rate.

$$\frac{\text{Number remaining} \times 1.74 \times 10^{-4}\,\text{Hz/m}^2 \times \text{Surface area of SK}}{\text{Number generated}}$$

$$\frac{49 \times 1.74 \times 10^{-4}\,\text{Hz/m}^2 \times 7,538\,\text{m}^2}{1,000,000} = 6.44 \times 10^{-5}\,\text{Hz}$$

$$\text{Event rate} = 6.44 \times 10^{-5}\,\text{Hz}$$

$$\text{Event rate} \times \text{Lifetime of SK7} = \text{Number of events}$$

$$3.49 \times 10^{7}\,\text{seconds} \times 6.44 \times 10^{-5}\,\text{Hz} = 2.25 \times 10^{3}\,\text{events}$$

$$2,250\,\text{IBD-like events during the lifetime of SK7}$$

Comparison with Izumiyama-san analysis (Analysis on real SK7 data's background): The observed number of events suspicious as neutron BG is 70 events/404.0 days. My own analysis estimates 30 times more
The event rate calculated depends on the muon spallation neutron flux around the Super-Kamiokande in the surrounding rock. One hypothesis is that the underground muon rate may not be entirely accurate or that neutrons could be captured before entering the SuperK tank. A current problem is the lack of a simulation for neutrons coming from outside and entering the tank. A potential solution to improve the neutron background prediction would be to perform measurements of the neutron flux on top of the Super-Kamiokande.

2.4 Technical work on the Super Kamiokande

As mentioned before, the last incident with the 5th magnetic coil requires repair work to regain its full efficiency. I had the opportunity to be part of the coil repair shift team by the end of July during one week. We achieved to fully repair the coil device meant to compensate geomagnetic field. This has been a great experience as a technician in one of the greatest Physics research project nowadays.

To prepare for possible other incident, it has been decided to install 6 new horizontal magnetic coils, in case another one should malfunction. The steps for every

coil are :
-Insert the cable in the outer tank and hang it to a winch
-Insert stainless steel pipes and attach it to the coil to make it an isocagon (twenty sided polygon).
-Winch down the coil inside the SK water

Figure 9: Photos of the coil work, by Nakahata-San [2]

The horizontal coil shift lasted from Friday 26th of July to Saturday 3rd of August and involved 40+ people. It is a real race against the clock as there is a risk of a supernova or another rare event occurring during the maintenance. This was a once in a lifetime opportunity to work on this shift and get inside the tank. This was the 6th and last time people entered the Super Kamiokande since its creation in 1996.

2.5 Responsibilities, challenges and skills developed

The most important part of my internship consisted in accumulating knowledge. Firstly to be efficient in my analysis and acquire a critical mind on my results, I had to understand how does the Super Kamiokande work and the physics used. Then, I had to learn about the tools that are used such as MAC terminal, vim, and root. Before working on my project I trained on multiple easier analysis and simulations to get used to the devices.

3 International Mobility

3.1 Motivations

My motivation for pursuing international mobility comes from a profound desire to expand my academic and cultural horizons in another country. I was eager to discover Japan and its culture. The Japanese culture has reached overseas countries and particularly France since the 60s with the interest for martial arts as Judo or Karate, and in the 90s with the surge of manga and anime. As I grew up with this cultural influence, I wanted to live a 3 months experience on the archipelago.

3.2 Challenges and skills developed

During my three-month stay in Japan, I encountered various challenges that significantly contributed to my personal and professional growth. One of the primary challenges was the language barrier. Despite having a basic understanding of Japanese, navigating daily interactions and academic environments, in a country where English proficiency is low, required me to adapt my language skills. I improved my abilities in both English and Japanese.

Culturally, adjusting to Japanese social norms and etiquette was challenging but somehow fascinating. For example, the work culture emphasize on emotional restraint. Contrary to Europe, there is almost no interactions between the seller and the customer therefore workers seem to be phlegmatic. However, this goes hand in hand with Japanese people's integrity and kindness: I experienced multiple moments when Japanese people dedicated their time to help me find my way for example; there is a climate of trust everywhere, you can see in cafes phone or laptop unattended, bicycle with no padlock, the most surprising are vendor-less thrift shops opened 24/7. I really felt comfortable in the culture and I am eager to come back to Japan one day.

Conclusion

Finally, the analysis highlighted the significant contribution of muon spallation to the Super-Kamiokande background noise, which is crucial for interpreting neutrino detection data. Nevertheless, the simulation cannot offer a quantitative results yet. But it shows that a significant part of the background can be caused by muon spallation.

In conclusion, my internship at Okayama University provided a unique opportunity to contribute to a cutting-edge research project while developing my knowledge and analysis skills. Through my work on analyzing muon spallation in the Super-Kamiokande detector, I gained a deeper understanding of particle physics and numerical methods. Additionally, the experience of working on the magnetic coil repair was an incredible opportunity and exposed me to large-scale collaborative scientific projects. This internship also offered a great international exposure, enriching both my academic and personal growth.

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[8] Results of 10 simulations of 10,000 events (Before cut)

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Abstract

For my second-year internship at Phelma, I worked on a project focused on Supernova Neutrino detection in Super-Kamiokande, in Okayama University. It is a large-scale neutrino observatory in Japan. The goal was to analyze the impact of muon spallation on the detector's background noise, a crucial element in the understanding of neutrino detection.

During this internship, I had to run an SKG4 simulation (a Geant4-based tool adapted for Super-Kamiokande), to study how muons interact with the detector and contribute to background events. My work involved analyzing data from the simulation, and applying cuts to isolate Inverse Beta Decay (IBD)-like events. The previous results from Koshio Sensei's group show that a significant portion of the background noise could be attributed to muon spallation. In fact, my analysis gives the same conclusion even though further ameliorations in the simulation are needed for quantitative results.

This internship not only allowed me to apply my knowledge in particle physics and data analysis but also offered an enriching cultural experience during my time in Japan.