Joint France-Japan PhD thesis proposal

Title: **Preparation of the Hyper-Kamiokande experiment – a unique observatory for rare events in the Universe**

2021-2024

LPNHE-Paris Neutrino group:

Jacques Dumarchez
Claudio Giganti
Mathieu Guigue
Boris Popov
Stefano Russo
Marco Zito

University of Tokyo (ICRR) group:

Yoshinari Hayato
Yusuke Kataoka
Yasuhiro Takemoto

University of Tokyo (Kavli IPMU):
Mark Hartz
Guillaume Pronost

The Hyper-Kamiokande (HK) experiment will be built in Japan by an international collaboration. The detector will hold 260000 tonnes of ultra-pure water – more than five times larger compared to the existing Super-Kamiokande (SK). The enormous size of the HK will enable it to detect unprecedented numbers of neutrinos produced by various sources — including cosmic rays, the Sun, supernovae and beams artificially produced by an existing particle accelerator. In addition to catching neutrinos, it will monitor the water for the possible spontaneous decay of protons in atomic nuclei, which, if observed, would be a revolutionary discovery. A joint team of physicists from LPNHE-Paris and University of Tokyo plan to contribute to both the detector construction via a precise time distribution and synchronization system and to the physics analysis via data calibration and reconstruction. Analysis of data already collected by T2K and SK would allow to calculate realistic sensitivities of HK experiment for neutrino oscillation parameters, including CP-violation phase. Additional hadron production measurements with the NA61/SHINE spectrometer at CERN would help reducing (anti-)neutrino flux uncertainties from the J-PARC accelerator.

Introduction

During the last decade the LPNHE-neutrino group has been involved in the T2K experiment which uses the Super-Kamiokande (SK) detector to register (anti)neutrino interactions from neutrino and antineutrino beams produced by the J-PARC accelerator. A close a fruitful collaboration has been established with Japanese phtsicists, including colleagues with the University of Tokyo. Recently, with the final approval of the Hyper-Kamiokande (HK) project by the Japanese government and endorsement obtained from the LPNHE Scientific Council, the LPNHE-neutrino group has also become involved in the HK experiment. The goal is to enlarge and to complement our current activities with studies of neutrinos from astrophysical sources using data from HK experiment. Indeed, full participation in the HK experiment will open a possibility for our group to study solar, atmospheric, supernovae neutrinos and by performing combined analyses of accelerator neutrino and antineutrino data with measurements of (anti)neutrinos from natural sources.

Contrary to T2K, which had access only to a subset of SK data in a small time window around the neutrino beam spill, the Hyper-Kamiokande experiment, hosted by the University of Tokyo, has a broad physics program covering many areas of particle and astroparticle physics. Based on the proven technology of (Super-)Kamiokande, its much larger detector volume and additional improvements in key areas like photosensors and near/intermediate detectors make HK a straightforward yet powerful extension of the very successful Japan-based neutrino program.

Right from the start of their history, the large Water Cherenkov detectors have been particularly successful in detecting neutrinos from astrophysical sources. Back in 1987, Kamiokande detected few neutrinos emitted by the famous 1987A supernova (SN) explosion, while in 1998 SK observed, for the first time, flavour oscillations of neutrinos produced in the atmosphere and in the Sun. The former observation opened a new window on neutrino astronomy and other exotic searches such as axion by constraining models describing the SN explosion mechanism, while the later proved the existence of neutrino oscillations predicted about 40 years earlier by Bruno Pontecorvo. More recently, new results from the T2K experiment using the muon neutrino beam from the J-PARC accelerator directed towards the SK detector conclusively showed that muon neutrinos transform to electron neutrinos, discovering appearance of new neutrino type in neutrino oscillations.

As the next-generation Water Cherenkov detector, Hyper-Kamiokande with a fiducial volume 8 times larger than Super-Kamiokande will start data taking by 2027. A new Cherenkov detector of 260 kton of water located 295 km down the muon neutrino beam generated by the J-PARC facility will be equipped with 20,000 20-inches photomultipliers (PMTs) with a large quantum efficiency. In addition, it is planned to install about 5,000 multi photomultipliers (mPMTs) that will enhance the detector capabilities at low energy. Indeed, the main advantage of the mPMTs is their improved timing resolution (from 2.6 ns for the 20-inches PMT to 1.6 ns for the 3-inches ones) allowing a reduction of the dark noise rate and an improvement of the spatial reconstruction efficiency. The team leader from the University of Tokyo – Dr. Yoshinari Hayato – is responsible within the collaboration for the working group developing PMT electronics and DAQ system.

HK, thanks to its gigantic mass, will detect thousands of electron antineutrinos (via inverse beta-decay) and electron neutrinos (via elastic scattering) from SN bursts in the galactic center.

Using the elastic scattering events, it will be possible to reconstruct the direction towards a SN at a distance of 10 kpc with an accuracy of about 1 degree. The events observed in HK will allow to provide detailed information about the time profile and the energy spectrum to further inspect SN explosion mechanism. In addition, it will be possible to detect neutrinos also from extra-galactic SN explosions. Even for distances of 4 Mpc, we will observe few tenths of neutrinos in HK and, at such distances, one SN is expected every three years. HK will also be able to detect the SN relic neutrinos (SRN) that are neutrinos produced by all SN explosions since the beginning of the universe. Such neutrinos fill the present universe and have a flux of few tens/cm^2/sec. The observation of SRN would allow understanding how heavy elements have been synthesized in stellar formation.

On top of that, HK will collect a large sample of atmospheric neutrinos. Such measurements will complement the long-baseline program and joint analyses between beam and atmospheric neutrinos are planned in order to improve the sensitivity to neutrino mass ordering and CP violation in neutrino oscillations. Indeed, the matter effects are rather small for the 295 km baseline of Tokai to HK making the sensitivity to the mass ordering limited, while atmospheric neutrinos emitted on the other side of the Earth and measured at the HK detector have crossed the Earth's core and experienced strong matter effects. Therefore, the HK detector as part of the Japanese long-baseline neutrino program will be extremely useful to further constrain neutrino oscillation parameters.

The success of this experiment relies on the excellent reconstruction of incoming neutrino energies and directions using the PMTs. The detection of SN events strongly depends on the reconstruction of the associated low-energy events and on the synchronization of HK PMTs and other experiments around the world. Moreover, reconstruction of neutrino interaction vertices in the detector requires an accurate timing determination of the event occurrence. It is therefore essential that an excellent clock distribution system is built for distributing and synchronizing time among all the detectors. Preliminary studies indicate that the timing precision should be lower than 1 ns with a maximum jitter of 100 ps RMS along with the capability of sending data using this link thanks to a sufficient bandwidth. Several solutions are under consideration at present, but two of them seem to be the most promising. One is based on the CERN White Rabbit (WR) protocol and the other on a custom solution.

World-wide, several detectors currently running or nearing completion are sensitive to a core-collapse supernova neutrino signal in the Milky Way using the so-called SNEWS (SuperNova Early Warning System) network. The neutrino burst signal emerges promptly from a supernova's core, whereas it may take hours for the first photons to be visible. Therefore, the detection of the neutrino burst from the next Galactic supernova can provide an early warning for astronomers. Requiring a coincident signal from several detectors will provide the astronomical community with a very high confidence early warning of the supernova's occurrence.

This thesis will be dedicated to the time synchronization of the photodetectors within the HK far detector. The impact of synchronization precision on the low energy physics including SN will be studied and will provide motivated requirements for HK. From this, the implementation and characterization of a suitable solution will be done on several experimental setups in view of later integration. New algorithms based on Machine Learning techniques will be developed and tested for reconstructing low energy Cherenkov rings induced by SN neutrinos. Finally, the HK detector will be integrated into a worldwide network for SN detection.

Research plan

This PhD thesis will be co-directed by Boris Popov (DR CNRS) and Mathieu Guigue (MdC Sorbonne Université), members of the LPNHE-neutrino group, and by Yoshinari Hayato from the ICRR, University of Tokyo. It is important to mention that M.Guigue has recently obtained a Sorbonne Université "Emergence" grant to work on technical developments towards the Hyper-Kamiokande experiment. The work of the student will also be coordinated with the development on time synchronization performed by experienced electronics engineer Stefano Russo (PhD Ingénieur de recherche, CNRS) working at LPNHE who has recently been nominated as a co-convener of the HK-Electronics working group.

Sharing common expertise between French and Japanese groups will guarantee full support and guidance to the PhD student who will spend a significant fraction of time at the University of Tokyo, thus profiting from exciting and stimulating environment of both laboratories.

A detailed research plan is as follows.

First year: studies and development of a time synchronization system for HK

One of the contributions foreseen by the LPNHE group to the Hyper-Kamiokande experiment is related to the communication block and, in particular, to the time synchronization and clock distribution for both the large PMTs and mPMTs since it represents a critical part of the experiment and we do have, in our electronic group, experts on this kind of technology.

The experiment's TDCs or FADCs timing synchronization is crucial for precise measurements of photon arrival and the actual requirement is set to have timing resolution of the photo-sensors at the level of 1 ns with a maximum jitter of 100 ps RMS. The distribution of a clock signal, synchronous with the GPS and a local atomic clock, to all Front-End (FE) nodes plus some signals to align FE's local counters call for a system structured as a data exchange protocol to transfer physics related information or slow control. Several solutions are under consideration at present. One is based on the CERN White Rabbit (WR) protocol and the other on a custom solution.

The White Rabbit protocol developed by CERN implements a fully deterministic gigabit ethernet-based network for general-purpose data transfer and sub-nanosecond accuracy time transfer. The link, from the timing distribution point of view, is structured as single-master-many-slaves using 18 ports' network switches and has sufficient bandwidth to allow time synchronization and data transfer including slow control. A White Rabbit node can be also connected inside a standard Ethernet network. A possible architecture for the HK experiment could be constituted by a series of switches, the one defined as master receiving the GPS's signal and distributing the clock to all the others via a daisy chain connection. Each switch of the chain can be connected to a maximum of 8 FEs and the other ports are used as a link to the data acquisition system. From this description it is clear that the White Rabbit represents a very attractive solution for the experiment also considering that the protocol is developed and maintained by CERN and the firmware and the hardware designs are distributed freely.

Another architecture is based on a custom design that takes advantage from a very specific configuration mode present in almost all the high speed serializer-deserializer embedded in modern FPGAs. Japanese collaborators are actively developing this mode that allows the realization of a high-speed point-to-point connection between two nodes using SK technology.

Recently, we have established close collaboration with physicists from the SYRTE laboratory at the Paris Observatory. This is very important for the project described above as SYRTE colleagues have already accumulated a significant experience in precise time determination and clock synchronization between different locations. The HK experiment could largely profit from this know-how. This is crucial for the efficient inclusion of HK detector into the SNEWS network. In addition, a neutrino burst alert may be able to serve as a trigger for detectors that are not able to trigger on a supernova signal by themselves, allowing extra data to be recorded. Precise timing information will be used later for physics analysis.

The PhD student will work on the characterization of the time synchronization in the context of HK in collaboration with SYRTE and technical teams (including Stefano Russo) at LPNHE. The newly designed equipment will then be produced and tested with Front-End electronics being developed by our Japanese colleagues. The PhD student will also perform physics analysis to study the impact of precise timing on the quality of reconstructed events in the HK detector especially on low-energy SN events. This will require a development of new reconstruction algorithms based on artificial intelligence. Performance of those algorithms can be checked using already accumulated SK data with the help of colleagues from the University of Tokyo.

Moreover, data transfer, calibration and reconstruction scheme will be worked out using the very performant IN2P3 Computing Centre at Lyon. There is a possibility to contribute on the computing aspects by providing storage elements and computing resources to the T2K and HK collaborations, in addition to expertise on the distributed computing using DIRAC, a python-based software framework for distributed computing.

2nd year: Characterization and impact of mPMT on HK low-energy physics

Another possible contribution to the HK project is related to the mPMT development and tests. R&D on an alternative photosensor option based on mPMTs modules is actively being carried out by several countries (mostly Canada, Italy, UK) with the goal of providing up to a half of the photo-cathode coverage for HK. Their lower dark rate compared to the large 20-inch PMTs are making them great candidates for the detection of low-energy events, in particular increasing the sensitivity of HK to the up-turn of the ^{8}B spectrum of solar neutrinos, probing the MSW-LMA prediction in the transition region between vacuum and matter-dominated neutrino oscillations. Their design also allows better vertex reconstruction especially close to the water tank walls, increasing the detector fiducial volume.

Participation in the mPMT development and tests is particularly appealing for our group as we could profit from the existing KM3NeT expertise, from the developments and tests of the small PMTs for the JUNO experiment and from the presence of the Memphyno water tank at the APC laboratory in Paris to perform underwater tests of the mPMT modules.

The Memphyno setup is equipped with two layers of scintillators allowing the identification of cosmic muons crossing the water tank where the tested prototype sits. Initial tests have already started using a first mPMT prototype from Italy currently installed and taking data in water in the Memphyno setup. More mPMTs prototypes are expected to be produced over the next couple of years, and this facility will be of great use for a first in-situ characterization of their performances, while using the SU “Emergence” grant recently awarded to develop more detailed characterization capabilities.

The second year of the PhD program will thus be dedicated to the underwater tests of the mPMT prototypes currently under development using the Memphyno setup at APC. The results obtained with these tests could allow the student to further study the impact of the mPMT on the low-energy physics accessible for the HK detector and further develop appropriate reconstruction algorithms using Machine Learning techniques

3nd year: Combined oscillation analysis using SK atmospheric and T2K beam data, projected sensitivity of HK

The last year of the PhD will be dedicated to the extraction of new physics results from a joint analysis of T2K and SK data and to the calculation of the expected sensitivities for the HK project from a combination of atmospheric and accelerator data. Indeed, the combination of atmospheric data with neutrino beam data allows to better constrain the matter effects on the neutrino oscillation, thus leading to a better constraint on the neutrino oscillation parameters. The results of this combined analysis and the projected sensitivity of the HK experiment will be presented at international conferences and in peer-reviewed papers.

Finally, starting from February 2023, the student will focus on the preparation of the PhD manuscript, with an expected defense in September 2023.