Joint France-Japan PhD thesis proposal

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

2021-2024

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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 the Sun, supernovae, cosmic rays and beams artificially produced by an existing particle accelerator. In addition to catching neutrinos, it will monitor the water for a possible spontaneous decay of protons in atomic nuclei, which, if observed, would be a revolutionary discovery.

Profiting from the newly created International Research Laboratory (IRL) a joint team of physicists from LPNHE-Paris and University of Tokyo plans to contribute to the HK detector construction via a precise time distribution and synchronization system and to the physics analysis via data calibration and reconstruction. Developed prototypes will be tested insitu in SK which is also a far detector of the currently running T2K-II experiment. In parallel we also contribute to additional hadron production measurements with the NA61/SHINE spectrometer at CERN which would help reducing (anti)neutrino flux uncertainties from the J-PARC accelerator. All these improvements would allow to calculate realistic sensitivities of HK experiment for neutrino oscillation parameters, including CP-violation phase.

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 and fruitful collaboration has been established with Japanese physicists, including colleagues from 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 HK data. 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 a 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 detector of 260 kton of water located 295 km down the muon neutrino beam generated by the J-PARC facility will be equipped with more than 20,000 20-inches photomultipliers (PMTs) with a large quantum efficiency. In addition, it is planned to install several thousands of 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. The HK project technical coordinator at LPNHE Dr. Stefano Russo has also been recently nominated *as a co-convener of the HK-Electronics working group.*

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.

For detection of accelerator neutrinos, events registered in a far detector (SK or HK) should also be well synchronized with the J-PARC accelerator timing. Moreover, to enhance physics performance of the HK experiment it is really crucial to reduce as much as possible uncertainties on the knowledge of (anti)neutrino fluxes. For this purpose, additional hadron production measurements with a replica of the neutrino production target currently in use at J-PARC are being considered. The NA61/SHINE spectrometer at CERN has a unique possibility to perform such measurements, and physicists from LPNHE have already accumulated a significant experience in the course of the T2K experiment. We will continue our involvement in this project during the HK era since Dr. Boris Popov is acting as analysis coordinator for neutrino physics within the NA61/SHINE collaboration.

This thesis will be dedicated to the development of the time synchronization system for the HK experiment in view of its integration into a worldwide network for SN detection. The implementation and characterization of a suitable solution will be done on several experimental setups, including the existing SK detector. The impact of synchronization precision on the low energy physics including SN will be studied and will provide motivated requirements for HK. In parallel, additional hadron production measurements with the NA61/SHINE spectrometer at CERN will be performed in order to reduce (anti)neutrino flux uncertainties from the J-PARC accelerator. All these improvements would allow to calculate realistic sensitivities of HK experiment for neutrino oscillation parameters, including CP-violation phase.

Research plan

This PhD thesis will be co-directed by Boris Popov (DR CNRS) and Stefano Russo (PhD Ingénieur de recherche, HDR, CNRS), members of the LPNHE-neutrino group, and by Yoshinari Hayato from the ICRR, University of Tokyo. The hardware part of the student’s work will be devoted to the characterization of the clock distribution and time synchronization system for HK and its tests for the UTC time base generation within the existing SK setup. It will be complemented with the analysis of newly collected NA61/SHINE hadron production data and their usage for improved prediction of accelerator neutrino fluxes in T2K-II and HK experiments.
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 and newly created International Research Laboratory (IRL), thus profiting from exciting and stimulating environment of both laboratories.
A detailed research plan is as follows.

First year (2021/2022): studies and development of a time synchronization system for HK; analysis of new NA61/SHINE hadron production data
Since a couple of years, the LPNHE group is working on its main contribution to the Hyper-Kamiokande experiment which 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. Two solutions (custom and WR) are being actively explored.
We have already established close contacts 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 base production in the context of both SK and HK and the clock synchronization for HK in collaboration with SYRTE and technical teams at LPNHE. The newly designed equipment will then be produced and tested with HK Front-End electronics being developed in collaboration with 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. Performance of those algorithms can be checked using already accumulated SK data with the help of colleagues from the University of Tokyo.

The student will also be involved in the data taking with the NA61/SHINE spectrometer at CERN using a replica of the carbon target being used at J-PARC for neutrino beam production. He/she will then participate in the calibration and analysis of these data.

2nd year (2022/2023): Insitu tests at Super-Kamiokande; improved predictions of (anti-)neutrino fluxes for T2K-II/HK

The LPNHE group has already purchased the required GNSS equipment (antenna and receiver) which will be used for a precise time-base definition for the clock distribution system. First prototypes of the time distribution system are being produced now. This equipment can be tested in the current SK configuration in order to characterize the achievable precision of the UTC time base generation under real conditions close to its final location. The second year of the PhD program will then be dedicated to this task.

In parallel, the newly obtained NA61/SHINE hadroproduction measurements will be used for improved predictions of (anti-)neutrino fluxes in T2K-II/HK. The student is expected to participate in these activities.

3rd year (2023/2024): Analysis of SK data; impact of these improvements on the HK projected sensitivity

The last year of the PhD will be dedicated to the analysis of data collected at SK and to the study of the impact of all these improvements (better timing precision and improved flux uncertainties) on the expected sensitivities for the HK experiment. The results of this analysis and the projected sensitivity of the HK experiment will be presented at international conferences and in peer-reviewed papers.

Finally, starting from February 2024, the student will focus on the preparation of the PhD manuscript, with an expected defense in September 2024.