BERTHA: BettER Timing precision for Hyper-kAmiokande

I. Pre-proposal's context, positioning and objective(s)

1. From T2K to Hyper-Kamiokande

The fact that we observe more matter than anti-matter in the Universe is one of the most outstanding problems in our understanding of the physics laws. The discovery of time symmetry violating (or CP-violating) mechanisms could bring a piece to the puzzle. However, it turns out that the already identified sources of CP violation are not enough to account for the observed matter/antimatter asymmetry. A new possible source of CP violation could exist in the lepton sector and could be found by studying the neutrino and anti-neutrino flavour oscillation phenomena.

This phenomenon was discovered about 20 years ago by the Super-Kamiokande experiment [1] in Japan and the SNO experiment [2] in Canada. A phenomenological model [3] hypothesizing that neutrinos have non-zero but small masses and that flavour neutrinos states are a quantum superposition of these mass states was developed. It is interesting to note that since the first observation, the parameters of this model have been measured with a precision of about 10 % or better thanks to several experiments around the world. One of the remaining parameters is the amount of CP violation in this oscillation phenomenon, represented by a phase called "delta-CP".

Such parameter can be measured by observing the change in composition of a neutrino beam compared with an anti-neutrino beam. This is the technique used by the T2K (for Tokai-to-Kamioka) experiment: a near detector at J-PARC in Tokai and a far detector (Super-Kamiokande) in the Kamioka mine at a distance of 295 km measure the change in the flavour composition of a neutrino and an antineutrino beam at an energy around 600 MeV. Hints that CP symmetry is not conserved in neutrino oscillations were recently reported in the journal Nature by the T2K collaboration [4].

In order to confirm these results and obtain a precise measurement of the delta-CP phase, a new long-term program building on past experience was initiated in Japan.

First, the power of the 30-GeV protons' accelerator at J-PARC will be upgraded to 1.3 MW in several stages over the next couple of years. With this upgrade, the quantity of hadrons produced by the interaction of the protons on a carbon target will increase; this will create more intense neutrino and antineutrino fluxes needed for the experiment.

Secondly, this next generation experiment requires a flux uncertainty better than 5%, which can be achieved with a suite of precise detectors characterising the flux near its production point. The ND280 detector is a composite detector located 280 m down the neutrino beam and it is undergoing a major upgrade [5]. This upgrade will be completed by 2022 allowing a couple of years to acquire data as the beam intensity is being upgraded. The improved sensitivity of this upgraded detector will also provide more insightful data to constrain the neutrino cross-sections, which is essential to understand the far detector's detection efficiency for a few percent. In addition, an Intermediate Water Cherenkov Detector (IWCD) corresponding to a scaled-down version of the far detector and located 750 m down the neutrino beam will be built; its primary purpose is to further study the neutrino interaction cross-sections since it will be using the same target material.

Finally, a new far detector (HK) with a fiducial volume 8 times larger than Super-Kamiokande and composed of a cylindrical tank filled with 250 ktons of pure water entirely covered with 20,000 20-inch PhotoMutiplier Tubes (PMT) will be built. As a neutrino interacts with a water molecule, emitted charged particles will produce Cherenkov light that is detected by the PMTs. The energy spectra of the incoming neutrinos and anti-neutrinos are then computed after reconstructing the kinematics of each produced charged particle and used to measure the oscillation parameters such as the delta-CP phase.

The physics program of the Hyper-Kamiokande experiment is not limited to the measurement of oscillation parameters and the discovery of CP violation in neutrino oscillation: the far detector is also capable of detecting neutrinos from astrophysical sources. A phenomenon of interest is the so-called "solar up-turn" corresponding to the transition between vacuum and matter effects of neutrinos going through the Sun. This astrophysics program requires to reduce the detection threshold of neutrinos interaction events to below 3 MeV which is not possible with the baseline 20-inch PMTs. For that purpose, the detector will also be equipped with several thousands of modules composed of thirteen 3-inch PMTs called “multi-PMT", which have a lower design dark rate of 100 Hz.
The huge quantity of instrumented water also invites the search for rare events such as the proton decay as predicted by Grand Unified Theories or a neutrino burst coming from an exploding supernova like the one detected by Kamiokande in 1987 [6]. This generally requires a better control of the fiducial volume which in turn justifies a R&D towards improving the reconstruction and especially the timing precision of the collected Cherenkov light. Also, being able to coincide events detected in HK with other neutrino observatories around the world requires an exquisite precision on the Universal Time (UTC).
The project received in 2019 the approval from the University of Tokyo and the Japanese funding agency (MEXT) and the excavation of the hosting cavern and the construction of the far detector started in April 2020. After a couple of years dedicated to R&D and construction of the detector, the data taking campaign is expected to start in summer 2027.

2. Project scientific objectives

One of the most critical items for the success of the Hyper-Kamiokande experiment is the distribution of the same clock to all the inner and outer PMTs of the far detector and the capability to tag each event with the most precise Universal Time (UTC). To that effect, the LPNHE Neutrino group is leading the R&D on these two aspects, in collaboration with the University of Tokyo and the INFN Rome. Also, we working closely with The SYstèmes de Référence Temps-Espace (SYRTE) laboratory at the Observatoire de Paris which has strong expertise in the design and the characterization of time references.

The clock distribution has a very strong impact on the reconstruction capabilities of the Cherenkov light emitted in the water of the detector and collected by the PMTs. Indeed, much of the precision in the reconstruction of the neutrino interaction vertex is determined by the precision with which one can determine the time the Cherenkov light arrives at a given photomultiplier. Typically, the 20-inches PMTs for HK have a transit time spreading (TTS) of about 10 ns, while the 3-inch PMTs composing the multi-PMTs have a typical TTS of 1.3 ns. It is therefore essential that an excellent clock distribution system is built for distributing and synchronizing time among all the PMTs. 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 slow control data using this link thanks to a sufficient bandwidth. These numbers need to be confirmed with in-situ tests.
For that purpose, the so-called Water Cherenkov Test Experiment (WCTE) will be built at CERN. This experiment will use a beam of charged particles like pions, protons, muons and electrons directed onto a scaled-down version of Hyper-Kamiokande. The detector will be equipped with about 120 multi-PMT modules. With a data taking campaign starting in 2023, this experiment will be used to test the multi-PMTs and measure important physics processes which are necessary for HK detector modelling. Given the size of the detector and the need for a precise vertex reconstruction, it is essential that a precise clock distribution is performed. Therefore, we plan on deploying prototypes of the clock distribution system developed at LPNHE for HK. The postdoc hired with this ANR funding will work on the integration of this system in WCTE and perform the analyses required to extract multi-PMTs performance. The impact of the timing on reconstructed kinematics e.g. the vertex reconstruction will also be studied using simulations during the first year of the contract.

Concerning the UTC synchronization, the LPNHE has acquired a Global Navigation Sattelite System (GNSS) antenna capable of receiving the signals from different satellites constellations e.g., GPS, Gallileo and QZSS/Michibiki. Preliminary characterizations with SYRTE expertise will happen in 2021 in Paris. The integration of this global time synchronization system into the SK detector is planned late 2021 or early 2022 using part of the ANR funds to purchase missing equipment. After a successful integration, the postdoc hired with this ANR funds would develop solutions for correcting signals received from the satellites and achieving a better timing resolution. One aspect of this work is to develop methods to apply offline corrections on all the SK data based on the satellites in the field of view at the time of the events and corrections catalogues produced weekly by the SYRTE laboratory, which is something that does not exist at the moment on SK. If successful, these solutions will be later used when implementing the time synchronization system in the Hyper-Kamiokande detector. The characterization results will be presented at the Super-Kamiokande and HK collaboration meetings and published in a peer-reviewed paper.

Finally, as we mentioned earlier, the WCTE at CERN will provide unique datasets important for the modelling of the Cherenkov light profiles in water. Indeed, discrepancies in the GEANT simulation models for Cherenkov light production have been observed indicating unknown model uncertainties which should be understood and reduced as much as possible before the beginning of Hyper-Kamiokande. Moreover, WCTE will deploy various calibration methods in order to further calibrate the multi-PMTs response and to control both charged particles coming from the beam and cosmic muons. These calibration tools such as light injectors and photogrammetry will provide insightful datasets for calibrating relative locations of the small PMTs composing multi-PMTs along with linearity responses. The postdoc would then contribute to the analysis of these datasets and the extraction of the physics parameters required for Hyper-Kamiokande simulations along with the impact study of these PMTs characterizations on the Hyper-Kamiokande physics sensitivity. The WCTE results and the sensitivity studies performed during the course of this ANR will be presented at international conferences and in peer-reviewed papers.

With this ANR project, we plan on deploying the prototypes on the Super-Kamiokande far detector and on the Water Cherenkov Test Experiment (WCTE) at CERN. The funding will allow us to hire a postdoc dedicated to the R&D effort and the analysis of various calibrations and physics results from these experiments. These implementation and calibration in the first years of the ANR will be concluded with the preparation of the full documentation for mass production.

II. Partnership and project organization

The Neutrino group at LPNHE is composed of 5 permanent CNRS researchers, 1 Maître de Conférences, 1 CNRS PhD engineer, 2 CNRS bénévoles, 2 postdoc (2 years) and 3 PhD students (3 years) with high expertise in long-baseline physics. The LPNHE Neutrino group has been working on the Japanese accelerator neutrino program and the T2K experiment since 2006. Since the project approval in Japan and by the LPNHE Scientific Council in 2019, the Neutrino group is preparing its future contributions to the Hyper-Kamiokande experiment.

The BERTHA project will include the PI Mathieu Guigue and other members of the Neutrino group at LPNHE, namely Boris Popov, Claudio Giganti, Jacques Dumarchez, Lucile Mellet, Marco Zito and Stefano Russo. The PI will coordinate the overall project and the postdoc hired with this ANR funding in his.her analyses and instrumentation tasks. This new hire will reinforce the person-power currently dedicated to HK; indeed Lucile Mellet (PhD student at Sorbonne Université) was hired in September 2020 under the PI' supervision to work on the Hyper-Kamiokande experiment. Finally, Stefano Russo (CNRS PhD Engineer), who initiated the R&D on clock distribution for the Hyper-Kamiokande and became co-convenor of the Electronics and DAQ working group in the Hyper-Kamiokande collaboration in 2020, will coordinate the R&D developments for this project.

The project coordinator MG earned his PhD in 2015 and was employed as a Postdoctoral Research Associate by Pacific NorthWest National Laboratory (Washington, USA) from 2016 until 2018. He had leading roles on the Project 8 experiment at the University of Washington being the Experiment Coordinator and Analysis Convenor from 2016 until 2019. He has then been hired by Sorbonne Université in Paris as Maître de Conférences since September 2018 and joined the T2K activities of the Neutrino group at LPNHE.
Indeed, the group is deeply involved in the near detector ND280 of the T2K experiment and is leading the current upgrade of this detector: Claudio Giganti (CNRS) is the project leader of this current ND280 detector upgrade. MG is coordinating the ND280 Reconstruction working group and is involved in the T2K Oscillation analysis group. Finally, the group leader Boris Popov (CNRS) is leading convener of the software and analysis for the NA61 experiment at CERN providing crucial hadron production measurements for (anti)neutrinos flux production in T2K and HK. **The strength of this project resides in the strong expertise of the group in neutrino physics and in the electronic design in various experiments, including the currently-running T2K experiment.**

Synergies with other groups in France exist and will be reinforced with this proposal approval. First of all, the “Paris Federation” gathers the LPNHE, AstroPhysique et Cosmologie and Laboratoire Leprince Riguet (on Ecole Polytechnique campus) laboratories, along with the IRFU at CEA Saclay. LLR and LPNHE have been and are still collaborating for the last 10 years together on T2K, and this fruitful collaboration will continue over the duration of Hyper-Kamiokande. Another obvious synergy on the clock synchronization system and multi-PMTs R&D exists with our French collaborators at APC working on KM3Net: indeed, the HK multi-PMTs design is inspired by the modules used in KM3Net and the White Rabbit system is being used on KM3Net for clock distribution. This ANR proposal aims at supporting these common efforts and expertise sharing toward the success of Hyper-Kamiokande.
Finally, Hyper-Kamiokande is an international collaboration gathering countries all around the world. This clock and time distribution system development already associates several laboratories (INFN Rome and University of Tokyo) around the world under Stefano Russo’s coordination. This project would be a great opportunity to develop a strong collaboration with the University of Tokyo and for example a long-term students exchange program. Moreover, our proximity with CERN both geographically and in term of our current implications would allow us to have a strong impact on the WCTE experiment.

The funding of this ANR project would allow the scientific coordinator to secure the LPNHE group contribution to the Hyper-Kamiokande experiment, strengthen his team dedicated to the clock distribution system and improve the group’s visibility within the collaboration. More generally, this project’s approval would bring more exposure of Hyper-Kamiokande physics potentials to the French and international scientific communities.

References related to the project

[1] Fukuda, Y. *et al.* Evidence for Oscillation of Atmospheric Neutrinos. *Phys. Rev. Lett.* **81**, 1562–1567 (1998).
[2] Ahmad, Q. R. *et al.* Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.* **89**, 011301 (2002).
[3] Pontecorvo, B. Mesonium and antimesonium. *JETP Lett.* 33, 549–551 (1957).
[4] Abe, K., Akutsu, R., Ali, A. et al. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. *Nature* 580, 339–344 (2020), arxiv:2002.09323.
[5] The T2K-ND280 upgrade proposal. https://cds.cern.ch/record/2299599.
[6] Totsuka, Y. *et al.* Observation of a neutrino burst from the supernova SN1987a. *Nucl. Physics, Sect. A* **478**, 189–195 (1988).