Neutrino physics with Super-Kamiokande and Hyper-Kamiokande

In August 2020, the Super-Kamiokande (SK) collaboration, home to two Nobel Prize winners, finished adding Gadolinium (Gd) to the 50 ktons of water of its detector [1]. We are entering, without any doubts, an era of extraordinary research with this upgraded detector, whose flagship program is the search of the diffuse neutrino background produced by all the supernovae since the first moments of the Universe (DSNB). Its discovery would open up a new, unique field of study for high energy physicists and cosmologists: history of star formation, nucleosynthesis and stellar evolution etc.

Previous analyses are highly affected by the limited ability of SK to discriminate between neutrinos and antineutrinos. When interacting in SK through charged-current interactions, they both produce a hadronic component with an associated charged lepton. SK being non-magnetized, provides no simple way to discriminate between the lepton charges and therefore, the experiment relies on the hadronic information to separate neutrinos and antineutrinos. Below 1 GeV, this hadronic part is respectively a proton and a neutron in case of neutrino and antineutrino interactions. However, none of these particles can be detected in SK. As a result, most of SK analyses could not separate neutrinos and antineutrinos, which limited the otherwise excellent sensitivity of the experiment. The addition of Gd has finally allowed to lift all these limitations by discriminating neutrons from protons, and therefore unambiguously differentiate neutrinos from antineutrinos. Gd which has one of the largest neutron capture cross-sections, yields a rather clean signal made of a cascade of γ rays with a total energy of 8 MeV.

Before adding Gd to ultrapure water, the SK collaboration validated the concept with a demonstrator called EGADS, a 200-ton experiment analogous to a smaller version of SK. Overall, 13 tons of Gd were recently introduced into the SK tank to reach a concentration of 0.02% achieving a neutron capture efficiency of about 50% on Gd. In September 2020, we started to record the first neutron captures on Gd opening up a new area of discoveries. Since May 2022, the Gd concentration has been increased by a factor 3 for a capture efficiency of 75%.

Supernovas are the most powerful cosmic source of MeV neutrinos, the latter carrying about 99% of the binding energy released during the collapse of the star. About 88% of the detectable supernova "neutrinos" are indeed electron antineutrinos which interact through Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$. Even if in our galaxy, supernovas may be fairly rare (current estimation is about three per century), it is estimated that about 10^{17} supernovas have occurred over the entire history of the Universe. The low energy neutrinos (below 50 MeV) emitted from those events must have suffused the Universe, but so far, the DSNB remains unobserved. Its detection would be an unprecedented event and a major discovery of the 21$^{\text{st}}$ century. It would provide important insights into cosmology, the history of star formation, nucleosynthesis, and stellar evolution. The DSNB flux is proportional to the rate of all core-collapse supernovas, including optically dark "failed" supernovas that collapse to form black holes, a phenomenon that has not been observed yet. The DSNB spectrum shape would also provide a crucial calibration for numerical supernova models. SK has previously carried out searches for the DSNB without requiring the detection of a delayed neutron (or with a poor tagging efficiency with neutron capture on hydrogen) [2]. The DSNB signal is expected to be visible in the positron energy range about 10 to 30 MeV where the largest backgrounds come from the decay of "invisible" muons (below the Cherenkov threshold) and spallation. The Gd doping significantly reduces those backgrounds by allowing the detection in coincidence of both the positron and the neutron. It is worth pointing out that the previous searches set an integral flux upper limit of the order of the most optimistic theoretical predictions making realistic the discovery of DSNB within few years.

The Hyper-Kamiokande (HK) detector will be the successor of SK. With a fiducial volume eight times larger and improved reconstruction algorithms, based on an accumulated experience of more than 25 years with SK, this new highly versatile experiment will explore with an unprecedented sensitivity variety of physics topics in the MeV - TeV energy range. This includes, among others, physics related to solar and atmospheric neutrinos, supernovae neutrinos, diffuse supernovae neutrino background (DSNB), beam neutrinos and CP violation discovery, neutrino astrophysics, and the study of dark matter as well as proton decay and other baryon number-violating processes [3]. The hosting site, under the mountain close to SK, is currently being excavated for a data taking starting in 2027.

The neutrino team of Laboratoire Leprince-Ringuet (`https://llr.in2p3.fr/`) located at Ecole polytechnique was created in 2006 by Michel Gonin. It is currently composed by 5 permanent researchers and 3 PhD students with an expertise in both high (CP violation, mass hierarchy,..) and low energy (supernovae, reactor and solar) neutrino physics. We are involved in three experiments in Japan. We have contributed to the discovery of ν_e appearance from a ν_μ beam with the T2K experiment and provided the very first indications of CP violation in the lepton sector [4]. We joined the SK collaboration in 2016 in which our group has specialized in the low energy part of the experiment through the search for the DSNB signal (boosted decision tree, neural networks) and the simulation, evaluation and understanding of spallation backgrounds [5]. We are currently working on the development of the future HK experiment with the aim of taking responsability for the digitisation of all photo-multiplier tubes (PMTs) of the experiment. The associated electronics is based on waveform digitisation which opens new possibilities for HK physics. A first version of the readout system (based on the HKROC chip) is currently under testing at LLR, with its main characteristics being a large dynmaic range allowing physics from MeV to hundreds of GeV, an excellent charge and time resolution, as well as a negligible (< 100 ns) deadtime.

The selected candidate will participate in SK analyses as well as in the development and tests of the HK electronics. Regarding SK analyses, the selected candidate will – depending on their interests – bring a major contribution to our group's central activities in the search of the DSNB or the study of solar (MSW effect) or atmospheric (mass hierarchy) neutrinos oscillations. They could also follow a phenomenological work of developping new tools allowing the interpretation of a potential discovery of the DSNB and in particular the impact on the supernova models and the contributions of failed supernovae forming black holes without light emission. There is clearly a lack of phenomenological tools that could be exploited by physicists bridging the gap between theorists and experimentalists. This task should fill this gap and will have to be carried out in collaboration with theorists with whom we have excellent relationship. The current construction of HK offers an exceptionnal research potential and is extremely complementary with that provided by SK analysis. Together with the development of HK electronics, the candidate may also work on the development of new reconstruction algorithms which will be used in HK.

References

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