PROCEEDINGS OF SCIENCE

Hyper-Kamiokande experiment

Takuya Tashiro[a,*]

[a] *Research Center for Cosmic Neutrino (RCCN), Institute for Cosmic Ray Research, University of Tokyo*

E-mail: ttashiro@icrr.u-tokyo.ac.jp

The Hyper-Kamiokande experiment consists of a 260 kt underground water Cherenkov detector with a fiducial volume more than 8 times larger than that of Super-Kamiokande. It will serve both as a far detector of a long-baseline neutrino experiment and an observatory for astrophysical neutrinos and rare decays.

The long-baseline neutrino experiment will detect neutrinos originating from the upgraded 1.3 MW neutrino beam produced at the J-PARC accelerator 295 km away. A near detector suite, close to the accelerator, will help characterise the beam and minimise systematic errors.

The experiment will investigate neutrino oscillation phenomena (including CP-violation and mass ordering) by studying accelerator, solar and atmospheric neutrinos, neutrino astronomy (solar, supernova, supernova relic neutrinos) and nucleon decays.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

*Speaker

PoS(EPS-HEP2021)234

1. Introduction

Hyper-Kamiokande (HK) is the new generation underground water Cherenkov detector. It is designed to consist of a cylingrical tank with the diameter of 68 m and the depth of 71 m to store ultra-pure water of 258 kton, among which the fiducial mass is 188 kton. The tank is optically separated into 2 regions; inner-detector (ID) and outer-detector (OD) and OD works as a shield and a veto counter against the particles coming from outside of the detector. The construction of HK started in 2020 and it is scheduled to start taking data since 2027.

Charged particles passing through the ultra-pure water at the speed faster than light produce Cherenkov-light, which can be detected by PMTs attached to the supporting structure in the tank. HK makes use of 3 types of PMT; 20-inch PMTs for ID, multi-PMTs for ID, and 8-inch PMTs for OD. Cherenkov-light produced in the ID region is reconstructed as a ring, whose pattern reflects the momentum, position, direction, and the type of the particle. Fig.1 and 2 show the pattern of detected light in a single electron and muon events, respectively.

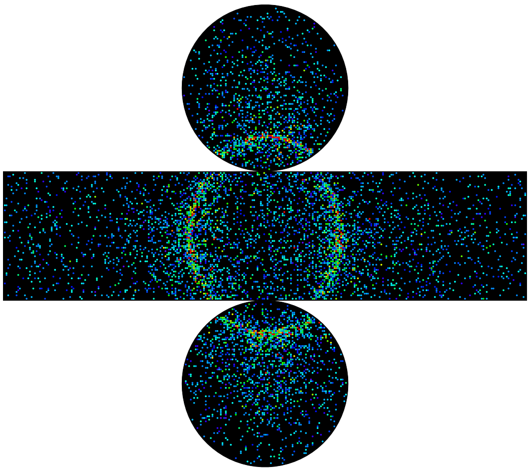

Figure 1: Simulated event of a single electron.

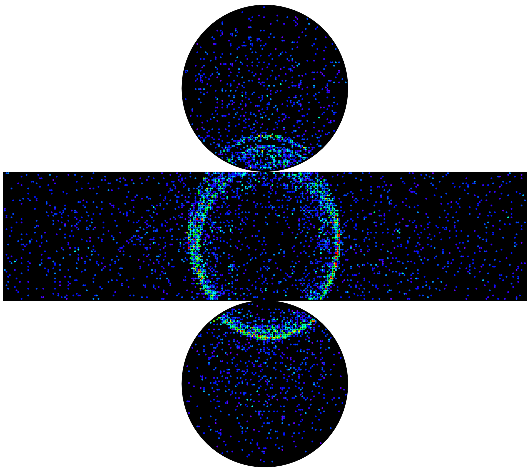

Figure 2: Simulated event of a single muon.

2. Physics goals

HK aims at revealing several important issues of cosmology and elementary particle physics.

2.1 Neutrino oscillation

Neutrino oscillation is a phenomenon that the type of the neutrino flavor changes during their travel. The probability of neutrino oscillation can be described by 6 parameters; 3 for mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$, 1 for CP phase δ_{CP}, and 2 for mass squared differences $\Delta m^2_{21} \equiv m^2_2 - m^2_1, \Delta m^2_{32} \equiv m^2_3 - m^2_2$, where m_i is the i-th eigenvalue of neutrino masses. The value of the CP phase and the sign of the mass squared difference are not yet determined. In HK, the parameters will be measured based on the accelerator and atmospheric neutrinos.

2.1.1 Accelerator neutrino

In the HK accelerator neutrino program, neutrinos generated in the accelerator facility of J-Parc, about 295km away from HK, travel to HK and the type of the neutrino flavor is determined to determine the probability of neutrino oscillation. The experimental method is similar to the ongoing T2K experiment, which makes use of J-Parc and Super-Kamiokande, the experimental setup including the neutrino beamline will be upgraded to enhance the accuracy of the measurement. In the upgraded program, the beam power, which was 515 kW in the T2K beam 2020, will be upgraded to 1.3 MW, and new intermediate water-Cherenkov detector will be installed in approximately 1km downstream from the beam line. New horizontal TPCs, scintillator target, and TOF detector will be additionally installed into the near detector system to improve the efficiency and the accuracy of the neutrino direction measurement. The data of the accelerator neutrino will be combined with the atmospheric neutrino data to determine the oscillation parameters.

2.1.2 Atmospheric neutrino

Interactions between primary cosmic ray and atmospheric nucleus produce atmospheric neutrinos with wide range of energies and pathlength. Measuring atmospheric neutrinos has an advantage in determining the the sign of Δm^2_{32}. The mass hierarchy with $\Delta m^2_{32} > 0$ is called "Normal" and with $\Delta m^2_{32} < 0$ is called "Inverted". Since the neutrinos penetrating the Earth are affected by the matter effect, which enhances $\nu_\mu \to \nu_e (\bar{\nu_\mu} \to \bar{\nu_e})$ oscillation in normal (inverted) hierarchy, the comparison between the neutrino and anti-neutrino oscillation can be used to determine the hierarchy.

The expected sensitivity of the mass hierarchy and δ_{CP} are shown in Fig.3 and 4. Both are expected to be determined within 10 years of operation.

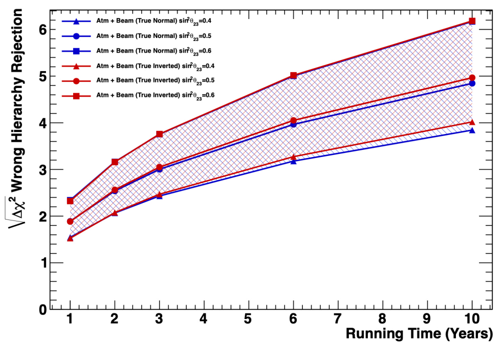

Figure 3: Expected sensitivity of determining the sign of Δm^2_{32}

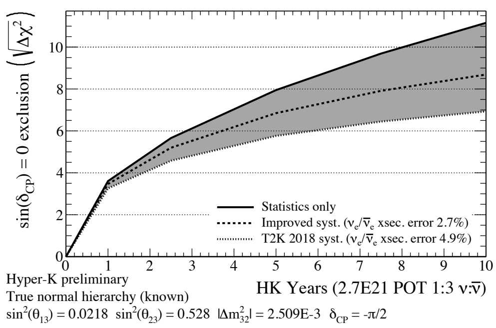

Figure 4: Expected sensitivity of determining the CP phase.

2.2 Nucleon decay searches

The nucleon decay phenomenon, which violates the baryon number conservation, is also one of the main physics goals in HK. HK has sensitivity to various decay modes and the search is expected to reach the proton lifetime predicted by various theories. The search by HK applies the event selection based on the kinematics of reconstructed Cherenkov rings. After the selection, the invariant mass and total momentum of the event is calculated using all the reconstructed rings and then the number of events in signal window defined in the mass-momentum plane is counted. The sensitivity of the search is expected to reach up to $5.0(1.0) \times 10^{34}$ years of lifetime in $e^+\pi^0(\bar{\nu}K^+)$ mode within 5 years of operation. The expected sensitivity in $e^+\pi^0$ and $\bar{\nu}K^+$ mode in HK and other future experiments are shown in Fig.5 and 6.

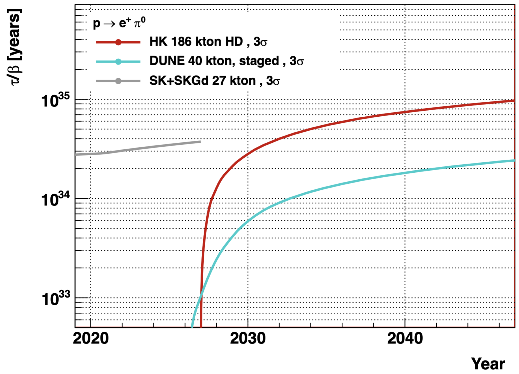

Figure 5: Expected sensitivity in the proton lifetime in e^+pi^0 mode.

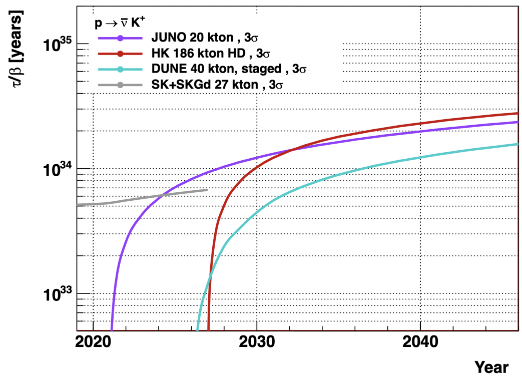

Figure 6: Expected sensitivity in the proton lifetime in $\bar{\nu}K^+$ mode.

2.3 Solar neutrinos

Solar neutrinos, originated from the nuclear reactions in the Sun, can be detected and measured by HK. In the solar neutrino system, the neutrino measured at night are affected by the terrestrial matter effect, which results in the day/night asymmetry. The solar neutrino measurement is also sensitive to the upturn of the spectrum, which is the variation of the ν_e survival probability between the vacuum and MSW-dominated energy region. It is not observed yet and can be a hint for the BSM physics. As the energy of solar neutrino is lower than the typical atmospheric and accelerator neutrinos, the performance of the study depends largely on the detector configuration including the photo-coverage and the energy threshold of the DAQ system. The sensitivity is simulated based on several possible detector configurations. In the day/night asymmetry measurement, the asymmetry is expected to be observed with $>5\ \sigma$ within 10 years of operation under the configuration with the photo-coverage of 20% and 40%. In the upturn analysis, the sensitivity is expected to exceed $5(3)\sigma$ within 10 years of operation with the threshold of 3.5(4.5) MeV. The expected sensitivity of day/night asymmetry and the upturn are shown in Fig.7 and 8.

2.4 Supernova and Supernova relic neutrinos

HK is sensitive to neutrinos related to supernova (SN). A core-collapse in SN is known to emit neutrinos as SN neutrinos. If it happens in our galaxy, large amounts of neutrinos are expected to be detected. The event rate of SN neutrinos is computed as a function of the distance between the Earth and SN. An order of 10k events is expected to be recorded if a SN happens in our galactic center, and an order of 10 events is expected if a SN happens in Andromeda galaxy, approximately 750 kpc away from the Earth. The expected number of events as a function of the distance is shown in Fig.9.

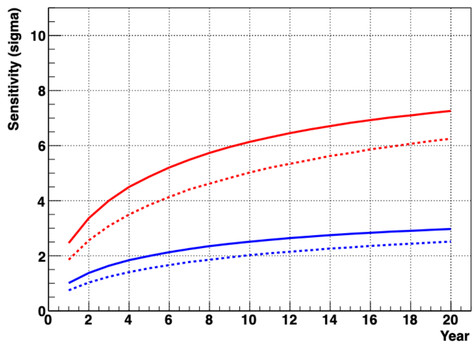

Figure 7: Expected sensitivity on the day/night asymmetry in the solar neutrino flux. The red and blue lines correspond to no asymmetry and the best-fit in the separation between the Δm^2_{21} measurement by KamLAND and solar neutrinos, respectively. The solid and dashed lines correspond the the photo-coverage of 40% and 20%, respectively.

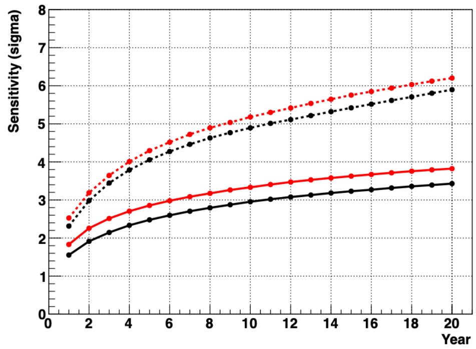

Figure 8: Expected sensitivity on upturn. The black and red lines were computed based on the best-fit value of neutrino oscillation in the solar analysis in 2019 and 2020, respectively. The solid and dashed lines correspond to the threshold of 4.5 MeV and 3.5 MeV, respectively.

Supernova relic neutrinos(SRN), which are the diffused neutrinos emitted from the past SNe, will also be searched by HK. Their existence is widely accepted, while they have not yet been observed. The measurement of SRN can be new tool to explore the history of the universe. Since the flux of the SRN is low compared to other processes, a neutron-tagging technique will be employed to reduce the background events and the sensitivity depends on the performance of it. Assuming that the neutron-tagging efficiency of 70% and mis-ID probability of 10% is achieved, approximately 70 events of SRN are expected to be observed within 10 years of operation. This corresponds to the sensitivity of $\sim 4\sigma$. The expected number of recorded SRN events in various neutron-tagging performance is shown in Fig.10.

3. Summary

HK, new water-Cherenkov detector with 188 kton fiducial mass, is being constructed and the operation will start in 2027. Various important physics topics including neutrino oscillation, nucleon decay, and neutrino astronomy will be explored by it. After 10 years of operation, HK is expected to conclude various questions including δ_{CP} and mass hierarchy in neutrino oscillation, the proton lifetime of 10^{34} years, day/night asymmetry and upturn in solar neutrinos, and existence of SRNs.

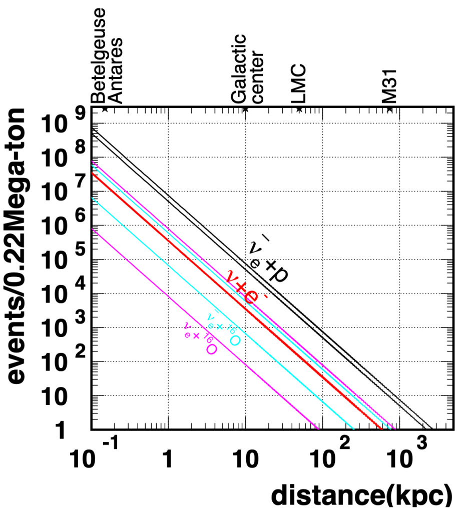

Figure 9: The expected number of recorded SN events as a function of the distance between the SN and the Earth.

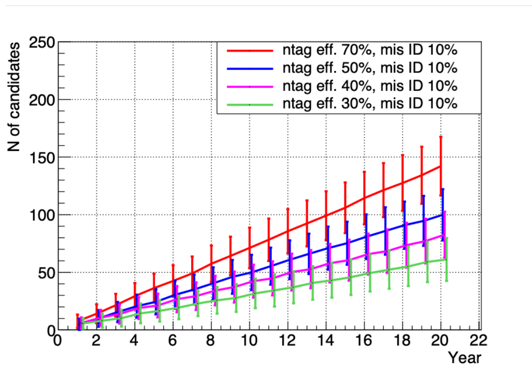

Figure 10: Expected number of recorded SRN events as a function of operating time.