Snowmass 2021 - Letter of Interest

The Hyper-Kamiokande Experiment

NF Topical Groups: (check all that apply ☐/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (NF7) Applications
■ (NF8) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors
■ (CF1) Dark Matter: Particle-like
■ (RF4) Baryon and Lepton Number Violating Processes
☐ (Other) *[Please specify frontier/topical group(s)]*

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Abstract:

Hyper-Kamiokande is the next generation underground water Cherenkov detector that builds on the highly successful Super-Kamiokande experiment. The detector which has an 8.4 times larger effective volume than its predecessor will be located along the T2K neutrino beamline and utilize an upgraded J-PARC beam with 2.6 times beam power. Hyper-K's low energy threshold combined with the very large fiducial volume make the detector unique, that is expected to acquire an unprecedented exposure of 3.8 Mton·year over a period of 20 years of operation. Hyper-Kamiokande combines an extremely diverse science program including nucleon decays, long-baseline neutrino oscillations, atmospheric neutrinos, and neutrinos from astrophysical origins. The scientific scope of this program is highly complementary to liquid-argon detectors for example in sensitivity to nucleon decay channels or supernova detection modes.

Hyper-Kamiokande construction has started in early 2020 and the experiment is expected to start operations in 2027. The Hyper-Kamiokande collaboration is presently being formed amongst groups from 19 countries including the United States, whose community has a long history of making significant contributions to the neutrino physics program in Japan. US physicists have played leading roles in the Kamiokande, Super-Kamiokande, EGADS, K2K, and T2K programs.

The Hyper-Kamiokande Experiment

Hyper-Kamiokande (Hyper-K)[1] is based on the highly successful Super-Kamiokande (Super-K) detector and takes full advantage of a well-proven technology. The detector will be located at the Tochibora site, 8 km south of the Super-K detector site. The cavern has a rock overburden of 650 m, corresponding to 1,750 meters of water equivalent (m.w.e.). The detector tank is 68 m in height and 71 m in diameter with a total volume of 258 kt. It is separated into an inner detector region containing 217 kt of water and an outer detector veto region. The inner detector is viewed by an array of 40,000 high QE Box & Line (B&L) PMTs with 50 cm diameter. The new PMT type has twice the photon detection efficiency compared to Super-K PMTs and with a better timing resolution of 2.6 ns (FWHM), and charge resolution of 30%. The dark rate is reduced to 4 kHz compared to 6 kHz at Super-K.

Hyper-K will receive the T2K neutrino beam from J-PARC at an off-axis angle of 2.5° on the opposite side of the beam. The beam power of the 30 GeV proton beam from the J-PARC Main Ring synchrotron will be upgraded from 515 kW (currently achieved for T2K) to 1.3 MW by increasing the number of protons per beam pulse and a higher repetition rate. The J-PARC beam power upgrade proceeds in stages and will be completed in 2028. Similar to T2K a ν_μ and $\bar{\nu}_\mu$ flux will be produced.

At the beginning of Hyper-K, three near detectors will precisely characterize the neutrino beam at J-PARC. The existing *ND280* detector will be upgraded[2] with fine-granularity plastic scintillator detectors, high angle TPC, and TOF detectors. With a larger angular acceptance and the 3D reconstruction capability of the new fine-granularity detector a significant reduction in the systematic uncertainty for oscillation analyses is expected. An *Intermediate Water Cherenkov Detector* (IWCD)[1] will be newly constructed at a 750 m distance from the neutrino production target. This one kiloton water Cherenkov detector can be moved vertically to measurement at different off-axis angles ranging from 4.0° to 1.0° off-axis angle. The main science goals include neutrino cross section measurements (3% for $\sigma(\nu_e)/\sigma(\nu_\mu)$ and 5% for $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$) and measurement of intrinsic electron neutrino backgrounds. The T2K on-axis near detector, *Interactive Neutrino GRID* (INGRID)[3], monitors neutrino event rates and measures the neutrino beam direction with a precision better than 1 mrad. INGRID is located at 280 m downstream from the production target will continue to be used for Hyper-K.

Nucleon Decay, Dark Matter, BSM Physics

Hyper-K will be able to provide some of the most stringent tests of the Standard Model. Nucleon decay sensitivities will be extended by one order of magnitude beyond the current limits and could reveal grand unified theories (GUTs)[1]. With 20 years of data, Hyper-K will reach a proton decay sensitivity of 10^{35} years for $p \to \pi^0 e^+$ and 3×10^{34} years for $p \to \bar{\nu} K^+$. These decay modes are highly complementary to those accessible by liquid argon based detectors.

The search for physics beyond the Standard Model of particle physics is one of the priorities of Hyper-K. Following Super-K's success the indirect search for dark matter from the Sun is expected to continue to provide the most sensitive tests for dark matter nucleon scattering for masses of a few a GeV in a model independent way[4–6]. Hyper-K can search for boosted dark matter[7] or test models with predominantly hadronic annihilation channels that remain hidden to other neutrino detectors[8–10]. Sensitivity of searches for dark matter from the Galactic halo will provide some of the best sensitivities to dark matter for annihilation channels with large neutrino yields. Precise oscillation measurements with atmospheric neutrinos can be used to push limits for Lorentz symmetry violation[11;12], non-standard interaction[13;14], quantum decoherence[15], sterile neutrino oscillation[16;17], and various dark sector particle searches such as heavy neutral lepton[18;19], long lived particle[20], and millicharged particles[21]. Non-standard neutrino interactions can be probed by Hyper-K using the neutrino beam and could be enhanced with a second detector in Korea[22;23].

Solar Neutrinos

Hyper-K, with its unprecedented statistical power, will be able to measure short-period flux variations in solar neutrinos, realizing a real-time monitoring of the Solar core temperature. Hyper-K could also achieve the first measurement of hep solar neutrinos, providing new insights in solar physics. The upturn at the vacuum-MSW transition region will be detectable at 5σ (3σ) with 10 years of data with an energy threshold of 3.5 MeV (4.5 MeV).

Astrophysics: Supernova Neutrinos, Multi-messenger science

Through the observation of $\sim$10 MeV neutrinos with time, energy and directional information, Hyper-K will take a unique role as multi-messenger observatory. Hyper-K will expand on the successful multi-messenger science program of Super-K[24]. It has the potential to detect thermal neutrinos from nearby (< 10 Mpc) neutron star merger events in coincidence with gravitational waves.

Hyper-K provides unique sensitivity to core-collapse supernova neutrinos[25–27] and is expected to detect more than 50,000 events for a Galactic supernova at 10 kpc. Hyper-K's reach extends to the Andromeda Galaxy M31 ($\sim$ 780 kpc) with about 10 to 16 events expected per supernova. The direction of a supernova at 10 kpc can be reconstructed with an accuracy of about 1° to 1.3° assuming similar event reconstruction performance as Super-K[1], making Hyper-K essential for distributing early alerts and multi-messenger observations. Further, even a few neutrinos from nearby extra-galactic supernovae can reveal the nature of transients whose mechanism is uncertain[28].

The search for diffuse supernova neutrino background (DSNB)[29;30] will aid our understanding of the rate and spectrum of typical supernova explosions. With the addition of Gd[31], Hyper-K could also separate $\bar{\nu}_e$ inverse beta reactions from other interactions. With Gd doping to tag $\bar{\nu}_e$ between 10 and 30 MeV and thereby distinguish supernova neutrinos from atmospheric neutrino backgrounds the sensitivity to DSNB can be significantly enhanced.

CP Violation, Neutrino Mass Ordering, Non-standard interactions

The apparent baryon asymmetry in our Universe is one of the greatest unsolved problems of our time. CP violation in the lepton sector could generate the observed matter-antimatter disparity through leptogenesis[32]. In 2020, the T2K[33] reported a measurement that favors large enhancement of the neutrino oscillation probability, excluding values of δ_{CP}, which result in a large enhancement of the observed anti-neutrino oscillation probability at 3σ. The result follows previous preference in global fits[34] but is in tension with NOνA[35].

With 10 years of running at 1.3 MW and split 1:3 between neutrinos and antineutrinos respectively, more than 65% of δ_{CP} can be excluded at 3σ given $\sin\delta_{CP} = 0$. A reduction in systematic uncertainties can further improve the sensitivity to δ_{CP}.

Using atmospheric neutrinos Hyper-K has sensitivity to determine the neutrino mass ordering due to the matter effects in the Earth. Sensitivity can be significantly enhanced with a detector in Korea[1]. The unitarity of the PMNS matrix can be tested through ν_τ appearance[36–38]. These oscillation results relies on precise neutrino interaction measurements by new near detectors[39–41]. These new measurement will push current knowledge of neutrino-nucleus scattering physics[42].

In a global context Hyper-K data combined with those from other long-baseline neutrino oscillation experiments will be essential to test non-standard oscillation scenarios, which can only be revealed by combining data from different experiments.

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