PROCEEDINGS OF SCIENCE

Astrophysical neutrinos in Hyper-Kamiokande

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Hyper-Kamiokande is a proposed next-generation underground large water-Cherenkov detector with a 187kton target volume of water and 40% photo coverage.With about 10 times larger fiducial volume than Super-Kamiokande, the sensitivities for astrophysical neutrinos, like solar or supernova neutrinos, but also contributions to multimessenger astronomy and dark matter searches, will be greatly improved in HyperK. The physics potential of HyperK on astrophysical neutrinos and its expected performance will be discussed.

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1. Introduction

The Hyper-Kamiokande (HyperK/HK) experiment[1] will be the next-generation water-Cherenkov multipurpose detector, and is expected to spearhead a number of complementary neutrino physics initiatives, including the long-baseline beam neutrino oscillation program T2HK (Tokai-to-HyperK) which will foreseeably also include an Intermediate Water Cherenkov Detector (IWCD) and, possibly, a second detector identical to HK further downstream at a longer baseline (sites in South Korea are being considered[2]).

HK will be a larger, improved version of the smaller Super-Kamiokande (SuperK/SK) detector, already in operation in the Kamioka underground laboratories since 1996 –currently in its newly-started SK-V data-taking period, and about to start its gadolinium-doped phase SK-Gd[3]–, only located in the new, nearby site of Tochibura.

HK is expected to provide pivotal contributions to a wide breadth of physics topics, and unparalleled sensitivities in many areas including (i) neutrino oscillations, with emphasis on determination of the neutrino mass hierarchy, the charge-parity (CP)-violating phase in the leptonic sector (δ_{CP}) and improved determination of other PMNS paradigm parameters, thanks to its T2HK long-baseline beam program, as well as atmospheric and solar neutrino studies; (ii) neutrino astrophysics (which will be further detailed in this paper), including (a) solar neutrinos (both solar neutrino spectrum and flare neutrinos), (b) supernova neutrinos (burst, pre-SN, Diffuse Supernova Neutrino Background (DSNB)..., (c) dark matter (DM) searches, and (d) other sources such as GRBs, GWs, AGNs... Also, HK will provide insights into (iii) neutrino geophysics and (iv) continue the search for nucleon decay, in particular the signature for proton decay, as Kamiokande and SK have done for decades.

2. HK design and capabilities

HK is designed as a 72 m-high, 68-m diameter cylindrical water tank (257.8 kt volume, see Figure 1) instrumented on its peripheral surfaces with photomultiplier tubes (PMTs) to provide 40% Inner Detector (ID) photocoverage. This will be realized with some combination of large box-and-line (B&L) Hamamatsu R12860-HQE 50-cm PMTs and multi-PMT modules comprising a set of nineteen 3-inch R12199-02 PMTs contained inside a watertight casing. HK is expected to offer the capability to collect as much as 10 times SK's statistics in the same amount of data-taking time, while aiming for a similarly low threshold thanks to comparable levels of background.

A superior energy resolution in a wide dynamic range is the critical factor in achieving HK's planned objectives, paired with the much-enhanced statistics collection. This projected energy resolution relies on achieving high precision calibrations and background suppersion (especially concerning ^{222}Rn) in line with SK's SK-IV period (2009-18). The new B&L PMTs provide commonality with SK's PMTs, both in shape and dimensions, while offering important improvements such as a $\sim$40% faster time response, a greater quantum efficiency at peak (+8%), greater Sb-K-Cs photocathode collection efficiency, improved single photoelectron (SPE) resolution, good resilience to saturation of its linear response – and mechanical enhancements, especially in the delicate neck area, allowing for twice the pressure-bearing resistance, improved shockwave-arresting

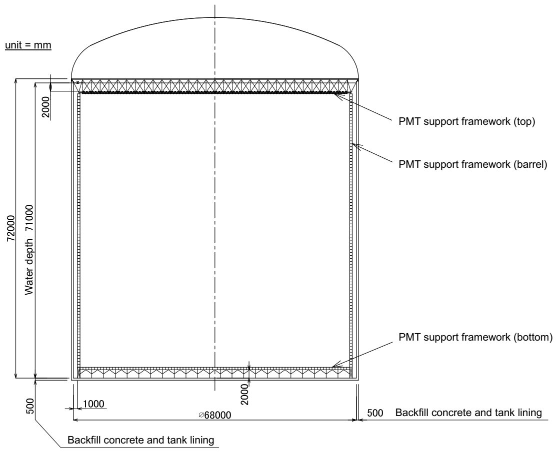

Figure 1: Vertical cross sectional view of the HK detector.

PMT covers, and an order of magnitude reduction in background (^{40}K). A dark rate reduction effort is ongoing to achieve lower rates comparable to SK-IV's, from the current $\sim$6 kHz.

3. Astrophysical neutrinos with HK

Hyper-Kamiokande will foreseeably provide higher statistics than any other planned next-generation neutrino detector, while keeping good directionality and sensitivity to low-energies, beyond just to ν_e.

3.1 Supernova neutrinos

HK will have pinpoint directionality capabilities (1-1.3°) and far reach into the cosmos to look for core-collapse supernovae (SN), which release $\sim 3{\cdot}10^{53}$erg (99%) of their energy in the form of neutrinos, offering up to 80,000 events in HK for a "neighborhood" SN at $\sim$10 kpc (see Figure 2), and capability to discern SN signatures up to $\sim$4 Mpc, with an expected low threshold of 3 MeV and stable data-acquisition for up to 50 kHz, an an expected signal every $\sim$3 years. It will be able to observe neutrinos from the $\sim$10 ms neutronization burst (ν_e), the $\leq$1 s-long accretion and cooling phases (all flavors of ν and $\overline{\nu}$, since inverse β decay (IBD) is possible), the black hole formation phase, as well as provide insights into the absolute mass of the neutrino. Furthermore, models of nucleosynthesis and more exotic collapse models (such as the controversial Standing Accretion Shock Instability (SASI)[5], which would imply neutrinos drive SN explosions) will be excluded or favored based on HK's observations. Other areas where HK will break new ground is in the detection of dim supernovae, collective inter-neutrino effects, the merged energy spectrum from extragalactic SN, or the shock breakout in interaction-powered SN, pointing toward the acceleration mechanism for galactic cosmic rays by SN remnants.

3.2 Diffuse Supernova Neutrino Background (DSNB)

The neutrino background left behind by all past supernovae in the history of the Universe, theorized to constitute a flux of $\Phi \sim$10 cm^{-2}s^{-1}, can tell the history of heavy element synthesis

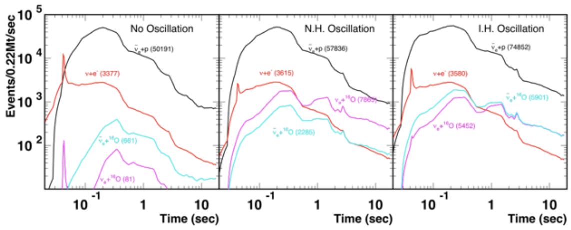

Figure 2: Time profile of supernova neutrinos in HK under different mass ordering conditions (center and right), with the unoscillated profile on the left.

since stellar formation commenced. It can in principle already be discovered by current-generation experiments (such as SK-Gd, since spallation products and low-energy atmospheric neutrinos obscure this flux in pure-water SK signals), but a megaton-scale experiment is needed to measure its spectrum and study its characteristics (see Figure 3).

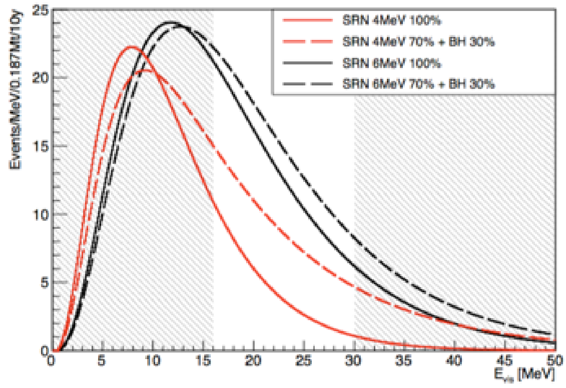

Figure 3: DSNB signal expectations in Hyper-K's fiducial volume over 10 years of data-taking. Black shows the case of neutrino temperature in supernova of 6 MeV, and red shows the case of 4 MeV. Solid line corresponds to the case in which all core-collapse supernovae emit neutrinos with that energy, while the dashed line considers 30% of the supernovae form a black hole and emits higher energy neutrinos, corresponding to the neutrino temperature of 8 MeV. HK sensitivity is the non-shaded area.

- **Neutron tagging** Neutron tagging is possible through its capture signal in hydrogen for pure-water detectors[4], but the efficiency of this technique is low ($\sim$50% estimated with the new high-efficiency HK PMTs). However, dissolving $\sim$500 tonnes of $Gd_2(SO_4)_3$ to attain a 0.1% concentration in HK, similar to SK-Gd's objective but with a much larger volume, would allow a 90% tagging efficiency for DSNB neutrinos (E$\sim$[16,30] MeV). Lowering the threshold to $\sim$10 MeV would allow for better time correlation (30μs) and vertex correlation (50 cm), allowing to access SN bursts down to the $z\sim$1 epoch.

- **SK-Gd** SuperK is about to start its gadolinium-doped phase in the SK-Gd program (mid-2020), after the leak present in SK-IV period to much less than 17 L/day (uncertainty limit) and the refurbishment and upgrade "tank-open" works performed during the summer of 2018. The SK-V pure-water data-taking period is now underway, during which time calibrations, exercising of the new water system and stabilization are ongoing, along with continuous data-taking for the regular SK and T2K programs.

- **HK-Gd** HK-Gd would allow to access pre-SN (O-Si burning) neutrinos beyond SK's current capabilities[6], better pinpoint capability for SN burst neutrinos, as well as improve sensitivity on δ_{CP}, proton decay and the DSNB flux characteristics – since all these studies benefit from better $\overline{\nu}$ sensitivity, which generate more final-state neutrons in their interactions by charge exchange.

3.3 Solar neutrinos

- **D/N asymmetry** The solar neutrino flux at night, in its high-energy part of the spectrum ($\sim^{8}$B), sees an enhancement due to the propagation of the neutrino flux through matter through the MSW effect. The much higher statistics of HK compared to SK (who discovered this effect[7]), together with a reduction in systematics (0.5→0.3%) thanks to low energy threshold and calibrations, can get 4σ evidence of the effect in as little as 2 years in HK, assuming SK's ^{222}Rn conent in the full FV, which while challenging is attainable, and reducing $\sim$3x the spallation background as compared to SK-IV's thanks to the improved photodetection efficiency allowing to better tag it away.

- **Upturn in the MSW transition region** The shape of the survival probability P_{ee} between low- and high-energy solar neutrinos (i.e. between the vacuum-dominated components *pp*, *pep* and ^{7}Be νs and the matter-enhanced component, mainly ^{8}B) can reveal information about Non-Standard Interactions (NSI), sterile neutrinos or other effects. This shape could be better measured thanks to the improved energy resolution in HK and background reduction. Together with the day-night asymmetry, this shape currently imply a tension in Δm^2_{12}, when including KamLAND's $\overline{\nu}$ data together with ν data (see Figure 4), which may be indicative of such new physics.

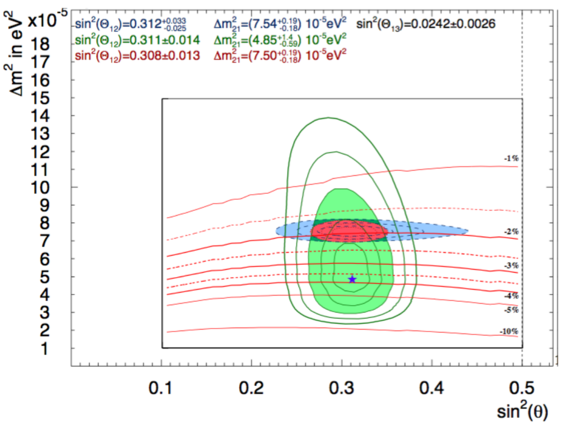

Figure 4: Allowed neutrino oscillation parameter region from all the solar neutrino experiments (green), reactor neutrino from KamLAND (blue) and combined (red) from one to five sigma lines and three sigma filled area. The star shows the best fit parameter from the solar neutrinos. The contour of the expected day-night asymmetry with 6.5 MeV (in kinetic energy) energy threshold is overlaid.

- ***hep* neutrinos** The smallest and most externally-produced spectral component of the solar neutrino flux, coming from the main *pp* chain, could be larger than expected by the SSM, and holds the second most important key to the Solar Metallicity Problem after CNO neutrinos, as well as to NSI above ∼18 MeV. It could be probed at the 2σ-level by HK within ∼12 years.

- **Solar variability studies** The statistical power of HK could provide a way to perform short-timescale variability analyses of the Sun's core temperature through ^{8}B ν's sensitivity to it, as they constitute a real-time sensitive "thermometer".

- **Solar flare neutrinos** Up to $\sim 10^{33}$ erg are emitted on a tens-of-minutes timescale when magnetic reconnections occur in the Sun, where protons can be accelerated up to 10 GeV. Interactions in the solar atmosphere can lead to mesons decaying into neutrinos. Even though large model uncertainties exist, up to 6-7 time-correlated events could be expected in HK, potentially leading to the discovery of this solar neutrino flux.

3.4 Multimessenger astronomy

HK would provide a new, extremely capable "eye" in the nascent field of multi-messenger astronomy, in particular with regards to **GRB jets and pulsar winds**, concerning their acceleration, composition, and connection between GRBs and energetic SN. GRBs possess a relativistic jet caused by a black hole's (or magnetized neutron star's) accretion disk, variable in the ∼ms scale, which produces unsteady outflows and shock dissipations, emitting prompt MeV γ rays, UHE cosmic rays and TeV/PeV neutrinos. The exact mechanisms at play are still debatable, but HK could detect a (possible, but unlikely) GRB at $<$100 Mpc, or alternatively (more likely) trans-relativistic SN or low-luminosity GRBs ("chocked jets"). Outflows need not be jets, as they can also be proto-neutron star winds ("newborn pulsar") heating neutrinos up to 0.1-1 GeV. Multimessenger astronomy would provide the crucial spatio-temporal reference to allow for coincidence searches and reduce atmospheric backgrounds to enable these detections. Also, **correlations with gravitational waves** could be expected for –presumably only– NS-NS mergers at $<$10 kpc, since models predict up to 10^{53} erg would be emitted in the form of neutrinos.

3.5 Dark Matter searches

Self-annihilation of dark matter particles in gravity wells could theoretically produce SM pairs ($W^{\pm}$, $\tau^{\pm}$, $\mu^{\pm}$ $b\bar{b}$, or interestingly for HK, $\nu\bar{\nu}$). The background for this kind of signal in HK would be atmospheric neutrinos, having ν_e and ν_μ components. However, discriminating through the angular distribution, similar to detecting the Sun in solar neutrinos, can point toward an excess coming from gravity wells such as the Galactic Center, the Earth or the Sun. The signal's momentum distribution would be a direct probe into the putative dark matter particle's mass, and HK would be sensitive to $\leq$100 GeV/c^2, as well as the self-annihilation cross section (3-10x SK's sensitivity, see Figure 5).

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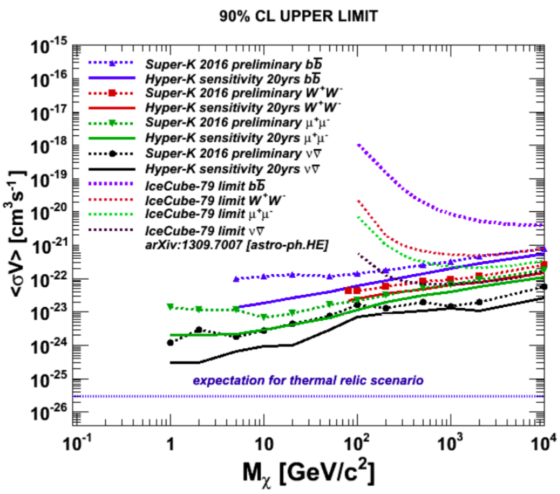

Figure 5: Hyper-K's expected 90% C.L. limit on the WIMP velocity-averaged self-annihilation cross section for several modes after a 3.8 Mtonáyear exposure overlaid with limits from several experiments.

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