

# Hyper-Kamiokande Physics Opportunities

Submitted by the Hyper-Kamiokande Working Group \*  
to the 2013 Snowmass Process

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## Abstract

We propose the Hyper-Kamiokande (Hyper-K) detector as a next generation underground water Cherenkov detector [1]. It will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC beam, and as a detector capable of observing, far beyond the sensitivity of the Super-Kamiokande (Super-K) detector, proton decays, atmospheric neutrinos, and neutrinos from astrophysical origins. The current baseline design of Hyper-K is based on the highly successful Super-K detector, taking full advantage of a well-proven technology. Hyper-K consists of two cylindrical tanks lying side-by-side, the outer dimensions of each tank being  $48(W) \times 54(H) \times 250(L) m^3$ . The total (fiducial) mass of the detector is 0.99 (0.56) million metric tons, which is about 20 (25) times larger than that of Super-K. A proposed location for Hyper-K is about 8 km south of Super-K (and 295 km away from J-PARC) at an underground depth of 1,750 meters water equivalent (m.w.e.). The inner detector region of the Hyper-K detector is viewed by 99,000 20-inch PMTs, corresponding to the PMT density of 20% photo-cathode coverage (one half of that of Super-K).

The Hyper-K project is envisioned to be completely open to the international community. The current working group contains members from Canada, Japan, Korea, Spain, Switzerland, Russia, the United Kingdom and the United States. The United States physics community has a long history of making contributions to the neutrino physics program in Japan. In Kamiokande, Super-Kamiokande, K2K and T2K, US physicists have played important roles building and operating beams, near detectors, and large underground water Cherenkov detectors. This set of three one-page whitepapers prepared for the US Snowmass process describes the opportunities for future physics discoveries at the Hyper-K facility with beam, atmospheric and astrophysical neutrinos.

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## Exploring CP violation with the upgraded J-PARC Beam

In 2011, the T2K [2], MINOS [3], and Double Chooz [4] experiments showed the first indications of full three-flavor oscillations. In 2012 the Daya Bay [5] and RENO [6] experiments reported the first precision measurements of the  $\theta_{13}$  mixing angle which drives three-flavor oscillation. This unexpectedly large value of  $\theta_{13}$  guarantees the ability to measure the CP violating phase  $\delta$ . The Hyper-K projects builds on the proven success of the water Cherenkov technique with an upgraded J-PARC beam plus a megaton-scale detector.

The J-PARC to Hyper-K experiment will use a proton beam with a  $\sim 1\text{MW}$  of power to produce both neutrinos and anti-neutrinos with a horn focusing system. The beam is directed  $2.5^\circ$  off-axis to the 560 kton fiducial volume Hyper-K detector 295 km away. The neutrinos are measured near the production site and then again at the far detector.  $CP$  violation will manifest itself in a difference between the measured rate of  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  transformations as well as in spectral distortions. The high event rate in the far detector will also allow for precise measurements of neutrino mixing parameters that will continue the worldwide effort to constrain the  $3 \times 3$  PMNS matrix.

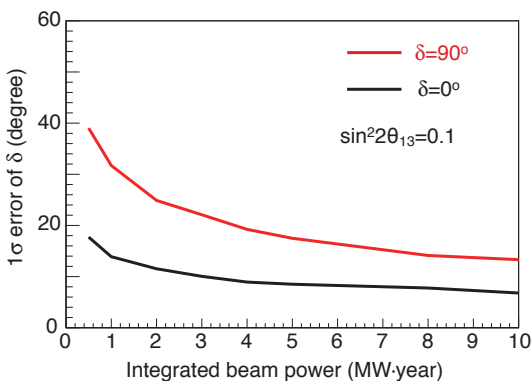


Figure 2:  $1\sigma$  uncertainty of  $\delta$  as a function of integrated beam power. The ratio of  $\nu$  and  $\bar{\nu}$  running time is fixed to 3:7.

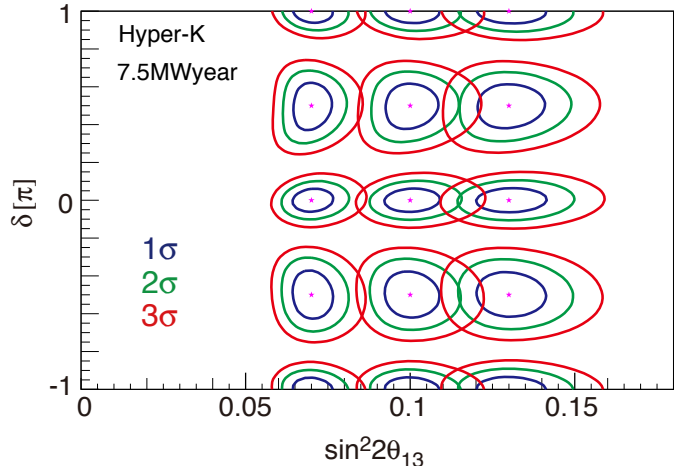


Figure 1: Allowed regions in the space of  $\sin^2 2\theta_{13}$  and  $\delta$  near the known value of  $\sin^2 2\theta_{13}$ . Blue, green, and red lines represent 1, 2, 3  $\sigma$  allowed regions in with the hierarchy known to be normal.

In 10 years of running, split 3:7 between neutrinos and antineutrinos respectively, we expect to collect approximately 2000 to 4000 signal events in each mode. Assuming the mass hierarchy is determined by other means, and that the total systematic error managed to the 5% level, then the CP phase may be distinguished from  $\delta = 0$  at  $3\sigma$  for 74% of the entire range in  $\delta$ . Figure 1 shows example  $1\sigma$  contours using the current range of  $\sin^2 2\theta_{13}$ . Figure 2 demonstrates the expected uncertainty in  $\delta$  as a function of integrated beam power for two values of  $\delta$ . After 7.5 MW-years,  $\delta$  will be measured with an accuracy between 7 and 15 degrees.

## Exploring Neutrino Properties with Atmospheric Neutrinos

In the late nineties, atmospheric neutrinos measured in the Super-Kamiokande detector provided the first definitive evidence that neutrinos had mass and that the mass states mixed to make the well known flavor states [7]. Atmospheric neutrinos remain an important probe of neutrino oscillations, and the large statistics sample from the one-half megaton Hyper-K will offer an unprecedented opportunity to study them in detail. Atmospheric neutrinos exist in both neutrino and anti-neutrino varieties in both muon and electron flavors. Approximately 1,000,000 events are expected to be collected in a 10 year period. The large value of  $\theta_{13}$ , along with the neutrino versus anti-neutrino dependent matter resonance effect in the earth opens up the study of oscillation driven electron neutrino appearance. The oscillation effect in the electron neutrino flux have been analytically calculated [8] as:

$$\begin{aligned} \frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx & P_2 \cdot (r \cdot \cos^2 \theta_{23} - 1) \\ & - r \cdot \sin \tilde{\theta}_{13} \cdot \cos^2 \tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos \delta \cdot R_2 - \sin \delta \cdot I_2) \\ & + 2 \sin^2 \tilde{\theta}_{13} \cdot (r \cdot \sin^2 \theta_{23} - 1) \end{aligned} \quad (1)$$

where we call the first, second, and third terms the “solar term”, “interference term”, and “ $\theta_{13}$  resonance term”, respectively.  $P_2$  is the two neutrino transition probability of  $\nu_e \rightarrow \nu_{\mu,\tau}$  which is driven by the solar neutrino mass difference  $\Delta m_{21}^2$ .  $R_2$  and  $I_2$  represent oscillation amplitudes for  $CP$  even and odd terms. For anti-neutrinos, the sign of the  $\delta$  should be changed. Additionally, the modified probabilities for  $P_2, R_2, I_2$  are obtained by replacing the matter potential  $V \rightarrow -V$  (see [8] for details). The electron appearance effect along with precision measurements of muon disappearance [9] and tau appearance [10] will allow Hyper-K to probe the octant of  $\theta_{23}$  oscillation, the mass hierarchy and  $CP$  violation phase.

A full Monte Carlo and reconstruction study using Super-Kamiokande tools has determined that the expected significance for the mass hierarchy determination is more than  $3\sigma$  provided  $\sin^2 \theta_{23} > 0.4$ . We expect to be able to discriminate between  $\sin^2 \theta_{23} < 0.5$  (first octant) and  $> 0.5$  (second octant) at the  $3\sigma$  level if  $\sin^2 2\theta_{23}$  is less than 0.99. For all values of  $\delta$ , 40% of the  $\delta$  range can be excluded at three sigma assuming that  $\sin^2 \theta_{23} > 0.4$ . All of these results are obtained using atmospheric neutrinos alone. In combination with the JPARC beam they can be even more tightly constrained. As an example, figure 3 demonstrates the sensitivity to the mass hierarchy as a function of  $\theta_{23}$  with  $\theta_{13}$  fixed at  $\sin^2 2\theta_{13} = 0.098$  for the case of the normal hierarchy.

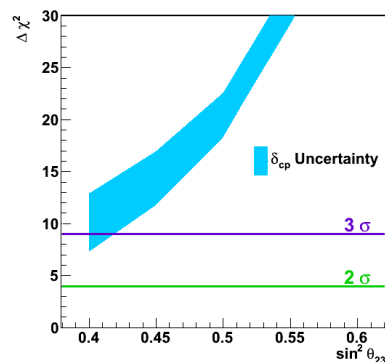


Figure 3: The sensitivity to the mass hierarchy as a function of  $\theta_{23}$  with  $\theta_{13}$  fixed at  $\sin^2 2\theta_{13} = 0.098$  (NH case).

## Low-Energy Neutrino Physics and Astrophysics with Hyper-K

Hyper-K represents the next generation of highly-successful water Cherenkov technology for observation of low-energy (less than  $\sim 50$  MeV) neutrinos, including solar neutrinos [11, 12, 13], core-collapse supernova neutrinos [14, 15, 16], and potentially dark matter annihilation neutrinos [17].

**Solar Neutrinos:** Assuming sufficient depth to overcome cosmic-muon-induced spallation background, Hyper-K will observe  $\sim 115,000$  elastic solar  $^8\text{B}$  neutrino-electron scatters per year (above its energy threshold and after event selection efficiency, assuming a livetime of 90%), an unprecedentedly large solar neutrino rate. With tight control of systematic uncertainties, Hyper-K will be very sensitive to the solar day/night effect, *i.e.* the regeneration of  $\nu_e$  flavor of solar neutrinos passing through the Earth. Within five years, Hyper-K will determine the solar zenith angle variation amplitude to  $\sim 0.5\%$ — expressed here as a day/night asymmetry, defined as  $(\text{day} - \text{night}) / (0.5(\text{day} + \text{night}))$ — measuring  $\Delta m_{21}^2$  with a precision comparable to that of current reactor antineutrino experiments, and establishing (or refuting) the presence of matter effects on neutrino oscillations with a significance exceeding  $4\sigma$  [18].

**Supernova Neutrinos:** Hyper-K is sensitive to neutrinos from Galactic core-collapse supernovae ( $\sim 250,000$  interactions in  $\sim 10$  s at the Galactic center a few times/century), nearby supernovae ( $\sim 25$  interactions at Andromeda; 1/2 interactions for distances  $< 4$  Mpc with  $\sim 60\%/25\%$  probability every few years) and distant supernovae ( $\sim 100$  interactions/year, up to  $z \sim 1$ ). With Gd salt doping [19], Hyper-K could also separate  $\bar{\nu}_e$  inverse beta reactions from other interactions. A large-statistics Galactic burst offers many unique opportunities (*e.g.* [20, 21] and references therein). From the time, flavor and energy profile of the neutrinos, we can learn about the neutronization burst, shock wave effects, explosion temperatures, and black hole formation. We may gain information on neutrino parameters, in particular mass hierarchy. Spectral swaps between neutrino flavors will enable the study of  $\nu - \nu$  interactions. In addition to an early alert for even quite distant supernovae, Hyper-K could also achieve precision pointing to a nearby supernova’s direction. Even a few neutrinos from nearby extragalactic supernovae will determine the nature of nearby transients whose mechanism is uncertain [22]. The rate and spectrum of distant supernova neutrinos characterize the properties of typical supernova explosions (luminosity and explosion temperature). For distant supernovae, Gd doping is essential to tag  $\bar{\nu}_e$  between 10 and 30 MeV and thereby distinguish supernova neutrinos from atmospheric neutrino backgrounds.

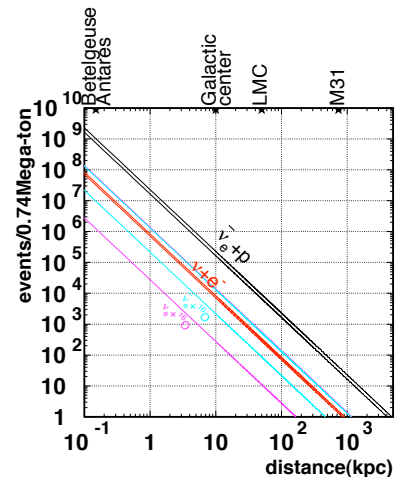


Figure 4: Expected numbers of SN burst events in HK for each interaction as a function of the distance to the SN [1].

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