Neutrino Astrophysics at Hyper-Kamiokande

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ICRR

Revealing the history of the universe with underground particle and nuclear research 2019

Tohoku Univ., 9th Mar. 2019
Hyper-Kamiokande Project

- Total Volume: 0.26 Mt
- Improved photo-sensors
- Construction will start at 2020. The measurement will be ready at 2027.

**Design**

<table>
<thead>
<tr>
<th></th>
<th>Hyper-Kamiokande</th>
<th>Super-Kamiokande</th>
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</thead>
<tbody>
<tr>
<td><strong>No. of PMTs (ID/OD)</strong></td>
<td>40,000 / 6,700</td>
<td>11,129 / 1,885</td>
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<tr>
<td><strong>Photocathode coverage</strong></td>
<td>40% (×2 efficient p.e. detection)</td>
<td>40%</td>
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<tr>
<td><strong>Total / Fiducial V.</strong></td>
<td>0.26 Mt / 0.19Mt (per tank)</td>
<td>50 kt / 22.5 kt</td>
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Hyper-K Site

- Hyper-K will be located in deep underground, Kamioka mine.
  - Super-K : 1 km vertical depth
  - Hyper-K : 640 m

- Simulation study for muon spallation backgrounds is done.
  Muon flux : Hyper-K = ~5 × Super-K
  Spallation product : Hyper-K = ~4 × SK
  new likelihood cut
  ~2.7 × SK
Neutrino, Messenger from Nature

Source of Neutrinos
- Solar
- Supernova
- Atmospheric
- Accelerator (J-PARC) (Geo & Reactor)

Physics of Neutrinos
- Neutrino Mixing
  - Mixing angles, Mass differences
- Difference between $\nu$ & $\bar{\nu}$
  - CPV, CPTV (Leptogenesis)
- Tiny neutrino masses
  - Mass hierarchy
- Astrophysics
  - Prove of supernova, Sun, Earth and our universe.
- $\nu$’s role in nature
  - $\nu$ heating in supernova
Astrophysical Neutrinos

Hyper-K (187 kton H$_2$O)
- $^8$B solar neutrino: 130 events / day
- Supernova neutrino: $\sim$50,000 events / burst
- Supernova relic neutrino: $\sim$18 events / year
- highest statistics / directional information

DUNE (40 kton Ar)
- Supernova neutrino: $\sim$3,000 events / burst
  sensitive to only electron neutrinos
- no directional information

JUNO (17 kton LS)
- Supernova neutrino: $\sim$5,000 events / burst
- Supernova relic neutrino: $\sim$3 events / year
- no directional information

IceCube (2,400 kton H$_2$O)
- Supernova neutrino: $\sim$300,000 events / burst
- no energy / directional information
Solar Neutrino

Real time measurement allowing solar neutrino spectroscopy

Cherenkov ring image in Super-K

Prospect in future solar neutrino

MSW matter effect of the neutrino oscillations in the Sun
Neutrino regeneration in the Earth (Day-Night effect)
Temporal flux variation / relation with solar activities
Branching ratio of nuclear fusion reactions

Hyper-K can address the issues
MSW Matter Effect

Required by observed energy dependence of survival probability ($P_{ee}$)

Energy dependence of survival probability

$$P_{ee} = \sin^2 \theta_{12} \ (\beta > 1, \ MSW)$$

$$P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta_{12} \ (\beta < \cos 2\theta_{12}, \ vacuum)$$

$$\beta = \frac{2\sqrt{2}G_F n_e E_\nu}{\Delta m^2}$$
Spectrum Up-turn

Intermediate energy region between vacuum and MSW oscillation (up-turn) can be measured more precisely in Hyper-K.

Survival probability of electron solar neutrinos

Sensitivity of energy spectrum up-turn

3.5 MeV threshold

4.5 MeV threshold

>3σ sensitivity


Observation of MSW oscillation with single neutrino source ($^8$B)

Test exotic scenario (non-standard interaction, sterile neutrino)
Day-Night Effect

zenith angle dependence of flux in Super-K

Super-K best
Solar + KamLAND

A. Renshaw et al.,
Phys. Rev. Lett. 112,
091805 (2014)

oscillation parameters : Solar and KamLAND

non-zero significance : 2.7σ

Goal of systematic error : 0.3%

>4σ for non-zero asymmetry & CPT invariance (P_ν = P_\bar{ν}) test
Hep Solar Neutrino

Three orders of magnitudes smaller than $^8$B solar neutrino flux

small branch
not detected yet

convection may enhance hep $\nu$ production at the high temperature core

$$^3\text{He} p \rightarrow ^4\text{He} e^+ \nu_e$$

First measurement of hep solar neutrinos at 2~3 $\sigma$

Test cross-section of He + p fusion, convection (non-standard SSM)
Confirmed that neutrinos bring most of the burst energy only in 10 sec.
Supernova Neutrino in Hyper-K

Main detection channels

Inverse beta decay
\[ \bar{\nu}_e + p \rightarrow e^+ + n \quad E > 1.8 \text{ MeV} \]
\[ \nu + e^- \rightarrow \nu + e^- \]
\[ \nu_e + ^{16}\text{O} \rightarrow e^- + ^{16}\text{F}(*) \quad E > 15 \text{ MeV} \]
\[ \bar{\nu}_e + ^{16}\text{O} \rightarrow e^+ + ^{16}\text{N}(*) \quad E > 11 \text{ MeV} \]

Total energy spectrum

galactic supernova at 10 kpc
54,000-90,000 events in total
high statistics
Time Modulation w/ Neutrino Oscillation

Normal Hierarchy (NH)
\[
\frac{dN_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = |U_{e1}|^2 \frac{dN_{\bar{\nu}_1}}{dE_{\bar{\nu}_1}} + |U_{e2}|^2 \frac{dN_{\bar{\nu}_2}}{dE_{\bar{\nu}_2}} + |U_{e3}|^2 \frac{dN_{\bar{\nu}_3}}{dE_{\bar{\nu}_3}}
\]

\[
= |U_{e1}|^2 \frac{dN_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} + (1 - |U_{e1}|^2) \frac{dN_{\nu_x}}{dE_{\nu_x}},
\]

Inverted Hierarchy (IH)
\[
\frac{dN_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = |U_{e3}|^2 \frac{dN_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} + (1 - |U_{e3}|^2) \frac{dN_{\nu_x}}{dE_{\nu_x}} \approx \frac{dN_{\nu_x}}{dE_{\nu_x}}
\]

Expected time profile (Livermore simulation) of a supernova at 10 kpc
Neutralization Burst

Unique feature in $\nu$-e scattering from neutralization burst supernova at 10 kpc (Livermore simulation)

$\nu_e$ emission for ~10 msec

shock wave propagation outward

dissociation of nuclei in free nucleon which triggers $e^-p \rightarrow \nu_e n$

shock wave pass through neutrinosphere

Hyper-K will observe the neutralization burst
Explosion Mechanism

First 0.3 sec after the onset of supernova burst

inverse beta decay for supernova at 10 kpc

onset time ~ 1 msec accuracy

Hyper-K will test the explosion mechanism, and investigate the core infall in conjunction with gravitational wave data.
Shock Revival by Neutrino Heating

Neutrino heating is a key phenomenon in the supernova explosion mechanism
- Shock wave from core bounce stalls in 100-200 km
- Neutrino heating revives the shock wave after $O(10)$-$O(100)$ ms

Some 2D and 3D simulations indicate SASI (Standing Accretion Shock Instability) is important process for the supernova explosion
SASI or neutrino-driven convection is controversial

SASI activity will cause the modulation in the accretion flow to the neutron star and the neutrino emission

Hyper-K will test the supernova neutrino flux modulation
- Amplitude of modulation depends on observer direction
- For the case of 3% amplitude of modulation, Hyper-K covers 90% of galactic supernova
Multi-Messenger Signals

complementary observation with 3 signals!

For the SN explosion, electromagnetic signal will delay in minutes to hours.

To obtain the electromagnetic signal follow-up, neutrino experiments need to predict the supernova direction as soon as possible.

global collaboration by SNEWS network

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global collaboration by SNEWS network

Only large water Cherenkov detector can measure the supernova direction

supernova @ 10 kpc

SK \( \Delta \theta_{SN} \sim 6^\circ \)

SK-Gd \( \Delta \theta_{SN} \sim 3^\circ \)

Hyper-K \( \Delta \theta_{SN} \sim 2^\circ \)

Pointing in 1.5 deg accuracy will allow the follow-up with large telescopes (> 1m)

\( \nu_e \rightarrow \nu_e \)

\( \bar{\nu}_e \rightarrow \bar{\nu}_e \) (dominant)
Supernova Relic Neutrino

star formation rate
(= core-collapse rate)

Neutrinos from supernova explosions in the early universe to the present day
integrated flux \( \sim 10 \text{ cm}^{-2}\text{ sec}^{-1} \) enough flux detectable in Hyper-K

Hyper-K will measure the average flux and energy in supernovae

\[
\frac{dF_{\nu}}{dE_{\nu}} = \frac{c}{H_0} \int_0^{z_{\text{max}}} R_{\text{SN}}(z) \frac{dN_{\nu}(E'_{\nu})}{dE'_{\nu}} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}},
\]

Neutron tagging effectively reduces the “invisible muon” background from atmospheric neutrinos → ×1/5

~70 events / 4σ detection significance in 10 years
Prospect

Relation with competing experiments to search for supernova relic neutrinos in the world

future projects: SK-Gd, JUNO, Hyper-K

number of SRN events in future projects

- SK-Gd (22.5 kton H$_2$O)
  - Low energy threshold: 10 MeV
  - Neutron tagging by Gd-loading
  - Start data-taking in 2018
  - Aim for the first discovery

- JUNO (17 kton LS)
  - Low energy threshold: 11 MeV
  - Start data-taking in 2020

- Hyper-K (187 kton H$_2$O)
  - Energy threshold: 16 MeV
  - Start data-taking in 2027
  - Aim for the precise flux and energy spectrum measurement

Hyper-K will be a leading experiment for supernova relic neutrinos
Star Formation History

- **core-collapse rate** predicted from star formation rate
- **observed supernova rate** visible supernovae

factor \( \sim 2 \) smaller than the expectation from star formation rate

→ invisible dim supernova or black hole formation?

Supernova explosions in massive stars (\( \sim 30 \) solar mass) result in **black hole formation, high E neutrino production**

Expected energy spectrum in Hyper-K (10 year)

- **neutrino flux**
  - solid line: NS only
  - dashed line: NS + BH
  - NS : BH = 70% : 30%
  - \( T = 6 \text{ MeV} \)
  - \( T = 4 \text{ MeV} \)

History of black hole formation can be investigated
Hyper-K with Gd

Option to add Gd compound in Hyper-K for neutron tagging

Energy threshold can be lowered from 16 MeV to 10 MeV

Explore the history of supernova burst back to red shift \( z \) \( \sim 1 \).

7.5x10^9 years
Summary

• Hyper-K will be a leading experiment in astroparticle physics research with the highest statistics and directional information
  – Our observation will start at 2027.
  – The detector design is being finalized.
• Astrophysical neutrino measurements is one of the features of Hyper-Kamiokande.
  – Solar neutrino
    • Hep neutrino, seasonal variation, up-turn etc…
  – Supernova neutrino
    • Energy and time spectrum measurement, SN alarming etc..
  – Supernova Relic Neutrino
    • Supernova and SFR models, extraordinary SN
Backup