Detection of supernova neutrinos at Super-Kamiokande

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Core-collapse supernova

Scenario of the core-collapse supernova

Core-collapse

\[ M \gtrsim 8 \text{M}_\odot \]

\[ e^- + p \rightarrow \nu_e + n \]

\[ Fe + \gamma \rightarrow p + n \]

Neutrino trapping

\[ \rho_c \sim 10^{12} \text{g/cm}^3 \]

Core bounce

\[ \rho_c \sim 3 \times 10^{14} \text{g/cm}^3 \]

Supernova burst

\[ E_{tot} \sim E_b^{NS} \sim 10^{53} \text{erg} \]

\[ E_{exp} \sim 10^{51} \text{erg} \]

Shock wave propagation

Shock wave at core

Figure from K.Sato
Expected neutrinos from core-collapse supernova

Released total energy: $\sim3\times10^{53}$ erg ($E_{\text{tot}}$)
Neutrinos carry out 99% of the energy
Burst kinetic energy: $\sim10^{51}$ erg (1% of $E_{\text{tot}}$)
Optical energy: $\sim10^{49}$ erg (0.01% of $E_{\text{tot}}$)

Iron core $\rightarrow$ neutron star / black hole

Neutrino emission is $\sim$ several seconds

Mean neutrino energy ($x=\mu,\tau$)

Luminosity

S. Nakazato et al., APJ supp.205:2(2013)

Neutrino and optical signals in supernova

Collapsed star

Neutrinos Travel with speed of light (3 x 10^5 km/sec)

Shock wave travels with ~1/30 of speed of light (~10^4 km/sec).

Optical signals are produced when the shock wave arrives at surface.

So, neutrinos arrive earlier than optical signals.
Type II: a few hours - several tens of hours earlier
Type Ib/Ic: several minutes earlier earlier
SN1987A: supernova at LMC(50kpc)

Kamiokande-II

IMB-3

BAKSAN

Japan Kamioka mine
2140ton fiducial
Water Cherenkov

USA Ohio state Morton mine
~5000ton Fiducial
Water Cherenkov

Russia Baksan tunnel
330ton in 3150tanks
Liquid scintillator

Although the observed number of events was only 24 in total, energy released by $\bar{\nu}_e$ was measured to be $\sim 5 \times 10^{52}$ erg.

It is consistent with core-collapse scenario.

But, no detailed information of burst process was obtained because of the low statistics.

We need next supernova with large number of neutrino events.
Super-Kamiokande detector

- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photosensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-V is running

Inner Detector (ID) PMT: ~11,000 20-inch PMTs
Outer Detector (OD) PMT: 1885 8-inch PMTs
The Super-Kamiokande Collaboration

~175 collaborators from 44 institutes in 10 countries
Typical low-energy event

Super-Kamiokande
Run 1742 Event 102496
96-25-31:07:13:23
Inner: 103 hit, 121 pE
Outer: ~5 hits, 0 pE (in-time)
Trigger ID: Om3
E = 9.086 GeV = 0.77 GOSL = 0.949
Solar Neutrino

Timing information
- vertex position
- ring pattern
- direction
- number of hit PMTs
- energy

E_{e, total} = 9.1 MeV

~6 hit / MeV

Resolutions (for 10 MeV electrons)
Energy: 14%
Vertex: 55 cm
Direction: 23°
Event reconstruction in water Cherenkov detector

- Timing and pulse height of each PMT are recorded.
- Reconstruct vertex position (i.e., interaction position) using timing information of PMTs.
- Reconstruct particle direction using the Cherenkov pattern (ring pattern with 42 deg. opening angle).
Neutrino interaction in water

Cross section (for H$_2$O)

Supernova $\nu$

Angular distributions

$\nu_e + p \rightarrow e^+ + n$

$\nu + e^- \rightarrow \nu + e^-$

$\nu_e +^{16}O \rightarrow e^+ +^{16}F$

$\bar{\nu}_e +^{16}O \rightarrow e^+ +^{16}N$
Super-K: Number of events

Number of events vs. distance


For each interaction

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Livermore</th>
<th>Nakazato</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\bar{\nu}_e p \rightarrow e^+ n)</td>
<td>7300</td>
<td>3100</td>
</tr>
<tr>
<td>(\nu + e^- \rightarrow \nu + e^-)</td>
<td>320</td>
<td>170</td>
</tr>
<tr>
<td>(^{16}\text{O} \text{ CC})</td>
<td>110</td>
<td>57</td>
</tr>
</tbody>
</table>

Supernova at 10 kpc
32kton water Cherenkov
4.5MeV(kin) threshold
No oscillation case.

Directional info.
Super-K: directional information

Reconstructed direction
(Simulation of a 10kpc supernova)

ν\text{e}+p \quad \nu+e

Distance vs. pointing accuracy

Livermore Model
- 3.1-3.8 deg. for 10kpc

Nakazato model
- 4.3-5.9 deg. for 10kpc
Sensitivity of Super-K for the model discrimination

10kpc supernova

Time variation of event rate

Time variation of mean energy

High statistics enough to discriminate models

Cooperation: H. Suzuki
Real time supernova monitor in Super-K

Raw data

Real Time Process
Quickly analyze events.
Reconstruct vertex, energy and direction.

SK shift people always keep watch whether the processes are running.

Processed data

Supernova Watch
Search for time-clustered events. Get initial result within 200 sec after a burst.

If significant time-clustered events are found, send e-mails to experts (PC and portable phone e-mails.) Also, send signal to SNEWS.

Details in K. Abe et al., Astropart. Phys. 81 (2016) 39-48
event cluster with >7MeV is found!

Is vertex distribution uniform? (i.e. not spllation?)

Yes

cluster size > 100 ?

Yes

Issue Golden Alarm

Discuss among relevant people with TV conference.
If real, send information (including direction, if possible) to ATEL, GCN, IAU-CBAT within one hour.

No

No

No

cluster size > 25 ?

Yes

Issue Normal Alarm

Discuss among experts. Hold a TV conference.

No

Issue Silent Alarm

Just send e-mail to experts. (happens ~2 times per day.)

Flowchart of action for a supernova in Super-K
Detection efficiency of the real time SN monitor

100% efficient for our galaxy and LMC for various models.

Gadolinium project at Super-K: SK-Gd

Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

\[ \bar{\nu}_e \rightarrow p + e^- + Gd^{2+} + \gamma \]

\[ \Delta T \sim 30\mu s \]

Vertices within 50cm

- 0.1% Gd gives ~90% efficiency for n capture
- In Super-K this means ~100 tons of water soluble Gd$_2$(SO$_4$)$_3$

- 0.01% Gd gives ~50% efficiency.
Physics with SK-Gd project

- Observation of Supernova Relic Neutrinos (SRN)
  - (also called Diffuse Supernova Neutrino Background (DSNB))
  - First observation is expected at SK-Gd

- Improve observation of supernova burst neutrinos
  - Improve pointing accuracy
  - $\nu_e (+\nu_x)$ spectrum measurement
  - Possible detection of neutrinos from Si burning.

- Reduce neutrino background for proton decays
  - Anti-tag neutrons to reduce atmospheric neutrino background

- Discriminate neutrino and anti-neutrino events for T2K
  - Using neutron multiplicity

- Reactor neutrinos
  - precise determination of $\theta_{12}$ and $\Delta m^2_{12}$ with high statistics measurement, if Japanese reactors restart
Supernova Relic Neutrinos (SRN)

$10^{22-23}$ stars in the universe ($\sim 10^{11}$ galaxies, $\sim 10^{11-12}$ stars/galaxy)

At present, we are getting neutrinos from $10^8$ supernovae every year.

We can study star formation history and averaged neutrino spectrum.
SK-Gd: Expected SRN signal and its significance


BG assumption
BG can be reduced by neutron tagging as follows:

- $\nu_\mu$ CC BG $\frac{1}{4}$
- $\nu_e$ CC BG $\frac{2}{3}$
- NC elastic BG $\frac{1}{3}$ (require only one neutron)

<table>
<thead>
<tr>
<th>Model</th>
<th>10-16MeV (evts/10yrs)</th>
<th>16-28MeV (evts/10yrs)</th>
<th>Total (10-28MeV) (/10yrs)</th>
<th>Significance (2 energy bin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HBD 8MeV</td>
<td>11.3</td>
<td>19.9</td>
<td>31.2</td>
<td>5.3 $\sigma$</td>
</tr>
<tr>
<td>HBD 6MeV</td>
<td>11.3</td>
<td>13.5</td>
<td>24.8</td>
<td>4.3 $\sigma$</td>
</tr>
<tr>
<td>HBD 4MeV</td>
<td>7.7</td>
<td>4.8</td>
<td>12.5</td>
<td>2.5 $\sigma$</td>
</tr>
<tr>
<td>HBD SN1987a</td>
<td>5.1</td>
<td>6.8</td>
<td>11.9</td>
<td>2.1 $\sigma$</td>
</tr>
<tr>
<td>BG</td>
<td>10</td>
<td>24</td>
<td>34</td>
<td>----</td>
</tr>
</tbody>
</table>
In case of Galactic supernova

Improve pointing accuracy

$\overline{\nu}_e$ w/o tagging

$\overline{\nu}_e + p$

$\nu + e$ scattering

$\overline{\nu}_e$ tagged with 80% eff.

(10kpc SN simulation)

If $\overline{\nu}_e$ can be tagged and subtracted from the plot, directional events ($\nu + e$ scattering events) can be enhanced and pointing accuracy can be improved.
Pointing accuracy can be improved by neutron anti-tagging.

Pointing accuracy with neutron information

Livermore Model

Nakazato model

Wilson model, SK-Gd
- Solid: with neutron anti-tag
- Dash: without neutron anti-tag

1.9-2.5 deg. for 10kpc with n anti-tag.
(3.1-3.8 deg. w/o that)

NK1 model, SK-Gd
- Solid: with neutron tag
- Dash: without neutron tag

3.3-4.1 deg. for 10kpc with n anti-tag.
(4.3-5.9 deg. w/o that)
Electromagnetic follow up

Optical magnitude

SK detector refurbishment in 2018

Purpose of the refurbishment

◆ **Fix water leak from the tank**
  About 1 ton per day of pure water leaked from the SK detector until 2018. We have sealed all welding joints of the stainless steel panels that make up the tank.

◆ **Improvement of tank piping**
  Ultra-pure water in the tank was circulated at a flow rate of 60 tons per hour before. We improved the water piping and water systems so that they can process and circulate water at 120 tons per hour. (17 days per one circulation).

◆ **Replacement of faulty photomultiplier tubes**
  Since the last in-tank SK maintenance during 2005-2006, some photomultipliers became faulty. We have replaced a few hundred PMTs.

The refurbish started from May 2018 and completed by January 2019.
Water Leakage check after refurbishment

After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31\textsuperscript{st} January to 15:52 on 7\textsuperscript{th} February, 2019. (7 days 4 hours 22 minutes in total)

Conclusion

- Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment.
Refurbishment: Water filling was completed in January 2019.

Plan to start 0.01% Gd run in early 2020. (Adjusting schedule with T2K)

<table>
<thead>
<tr>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>202X</th>
<th>202X+n</th>
</tr>
</thead>
<tbody>
<tr>
<td>work</td>
<td>Fill pure water (2.5 months)</td>
<td>Pure water Run</td>
<td>T&lt;sub&gt;1&lt;/sub&gt; : 10 ton Gd&lt;sub&gt;2&lt;/sub&gt;(SO&lt;sub&gt;4&lt;/sub&gt;)&lt;sub&gt;3&lt;/sub&gt;</td>
<td>0.01%Gd run ~50% n cap. eff.</td>
</tr>
</tbody>
</table>
High energy neutrinos at SK

Atmospheric neutrino spectrum

- Super-K measures atmospheric neutrinos in a wide energy range from 100 MeV to several TeV
- Overlap in high energy with AMANDA and IceCube regions

SK has the world largest sensitivity for <10GeV neutrinos.
High energy neutrino data samples

- Three event topologies: FC, PC, UPMU
- Sub-divided by particle ID, number of rings, stopping/through-going
- Different sub-sample provides different energy response
- Covers from sub-GeV up to 100 GeV (10 TeV) for $\nu_e$ ($\nu_\mu$) by combination of these samples
Angular Resolution

- Roughly tens of degrees on average for less than several GeV
- Better resolution (2~3 degrees) for UPMU sample in >10GeV due to high Lorentz boost
- Directional search is possible for high energy events above 10 GeV in <10 degree circle
Conclusions

• Large number of neutrino events is expected for a galactic supernova and they will tell us detailed information to reveal explosion mechanism.

• SK-Gd phase is being prepared. Main physics target is the detection of supernova relic neutrinos.

• SK-Gd will improve pointing accuracy for galactic supernova.

• The tank open work in 2018 stopped the water leak.

• The SK-Gd phase should start within one year.

• SK has the world largest sensitivity for <10GeV neutrinos.