Supernova neutrinos in SK-Gd and other experiments

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Abstract. Now many detectors are waiting for core-collapse supernovae in or near our galaxy. If they occur in our galaxy we will be able to reveal the mechanism of supernova explosions and also be able to access the properties of neutrinos, such as mass hierarchy. Even dark matter detectors can reach them via coherent elastic neutrino nucleus scattering; however no supernova neutrinos have been observed since February 1987.

Supernova explosions in our galaxy may be fairly rare, but supernovae themselves are not. On average, there is one supernova somewhere in the universe each second. The neutrinos emitted from all of these supernovae since the onset of stellar formation have suffused the universe. We refer to this unobserved flux as the “relic” supernova neutrinos. Theoretical models vary, but several supernova relic neutrinos (SRNs) per year above 10 MeV are expected to interact in Super-Kamiokande. However, in order to separate these signals from the much more common solar and atmospheric neutrinos and other backgrounds, we need a new detection method.

On June 27 2015, the Super-Kamiokande Collaboration approved the SK-Gd project. It is the upgrade of the SK detector via the addition of gadolinium sulfate. This modification will enable it to efficiently identify low energy anti-neutrinos for the world’s first observation of the SRNs via inverse beta decay.

1. Introduction

On February 23 1987, the Kamiokande [1], IMB [2] and Baksan [3] detectors recorded a pulse of neutrinos emitted by SN1987A. It had been predicted that almost 99% of the energy of the explosion is transported by neutrinos. The observation of neutrinos from SN1987A confirmed that this scenario is actually correct. The number of events observed in each experiment was 11, 8 and 5 in Kamiokande, IMB and Baksan, respectively. Although these are small numbers, it was possible to obtain some estimates on the binding energy of the neutron star remnant and the temperature of the neutrino sphere. The binding energy obtained from Kamiokande and IMB data assuming equi-partition (the released energy by each neutrino species is the same, i.e. the total energy is 6 times the energy released by $\bar{\nu}_e$) was $\sim 3 \times 10^{53}$ erg and is consistent with the standard scenario of the core collapse supernova. The $\bar{\nu}_e$ temperature obtained from Kamiokande and IMB data was $3.5 \pm 0.5$ MeV [4].

In order to investigate details on the supernova burst mechanism, the “next” nearby supernova is necessary. The distance to SN1987A was 50 kpc, so if the next supernova happens in our Galaxy, many more events are expected in the detectors deployed around the world.
2. Current supernova detectors

2.1. Water Cherenkov detectors

Super-Kamiokande (SK) is a water Cherenkov detector which has 32,000 ton fiducial volume for supernova neutrinos above 4.5 MeV. SK has potential to detect about 7,300 $\bar{\nu}_e p \rightarrow e^+ n$ events, $\sim 300 \nu + e \rightarrow \nu + e$ scattering events, $\sim 360 \ ^{16}\text{O}$ neutral current gamma events, and $\sim 100 \ ^{16}\text{O}$ charged current events for a 10 kpc supernova [5]. The $\nu + e \rightarrow \nu + e$ scattering events give the direction of the supernova with an accuracy of about 5°. The large statistics of $\bar{\nu}_e p \rightarrow e^+ n$ events gives a precise energy spectrum measurement, and it enable us to discuss models of supernova simulation.

IceCube has a giga-ton target volume and photo-sensors deployed in a three-dimensional-way within it. IceCube is not able to detect each neutrino event individually, but the burst can be observed as a coherent increase of PMT single rates [6]. Even for a supernova in the Large Magellanic Cloud (50 kpc away), IceCube can give 5$\sigma$ level signal.

2.2. Liquid scintillators

The detector with the longest operation is Baksan, which consists of 3,150 liquid scintillation counters with a total target mass of 330 tons [7]. About 100 $\bar{\nu}_e p \rightarrow e^+ n$ events are expected for a supernova at 10 kpc.

The LVD detector is a segmented liquid scintillator type detector with 840 counters and total target mass of 1,000 tons. It is able to detect about $\sim 300 \bar{\nu}_e p \rightarrow e^+ n$ events for a 10 kpc supernova [8]. The energy threshold of the counter is 4 MeV, and it is able to tag neutrons with an efficiency of 50±10%. The efficiency is more than 90% for distances below less than 40 kpc.

KamLAND [9], Borexino [10] and SNO+ [11] are single volume liquid scintillation detectors with 1,000 ton, 300 ton and 1,000 ton detection volumes, respectively, and are able to detect various interaction channels. The expected number of events for a 10 kpc supernova per 1,000 tons target mass is $\sim 300 \bar{\nu}_e p \rightarrow e^+ n$, several tens of CC and NC events on $^{12}\text{C}$, and $\sim 300 \nu p \rightarrow \nu p$ NC events. Among them, the neutral current interaction of $\nu p \rightarrow \nu p$ gives the original temperature of the $\nu X$ ($X=\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$) [12].

2.3. Other detectors

HALO uses a 76 ton lead target to liberate neutrons by charged current interactions ($\nu_e + ^{208}\text{Pb} \rightarrow ^{207}\text{Bi} + n + e^-$, $^{206}\text{Bi} + 2n + e^-$) and neutral current interactions ($\nu_x + ^{208}\text{Pb} \rightarrow ^{207}\text{Pb} + n$, $^{206}\text{Pb} + 2n$). Those neutrons are counted by low background $^3\text{He}$ counters used in the previous SNO experiment. About 40 neutron events are expected for a 10 kpc supernova.

Recently several ton-scale dark matter detectors have started or are soon expected to operate all over the world and these detectors are also sensitive to supernova bursts via coherent elastic neutrino nucleus scattering, such as $\nu_x + Xe \rightarrow \nu_x + Xe$. As an example, the expected event rates of XMASS [13] for a 10 kpc supernova is shown in Figure 1.

3. Future detectors

For the future, large volume neutrino detectors are proposed for long baseline accelerator neutrino experiments and reactor neutrino experiments.

Hyper-Kamiokande (HK) [14] is a 0.52-Mton water Cherenkov detector, and its fiducial mass for supernova neutrinos is 0.44 Mton, 14 times larger than that of SK. Figure 2 shows the expected number of supernova neutrino events at HK versus the distance to a supernova. In HK, about 100,000$\sim$140,000 inverse beta events, 4,200$\sim$5,000 $\nu e$-scattering events, 200$\sim$8,000 $\nu e^{16}\text{O}$ CC events, and 1,200$\sim$8,000 $\bar{\nu}e^{16}\text{O}$ CC events, in total 100,000$\sim$150,000 events are expected for a 10 kpc supernova. Even for a supernova in M31 (Andromeda Galaxy), about 20$\sim$30 events are expected at HK. In the case of the Large Magellanic Cloud (LMC), about 4,000$\sim$6,000 events are expected.
Figure 1. Simulation of the coherent elastic neutrino nucleus scattering signals of supernova burst at XMASS for a 10 kpc distant supernova. The green histogram shows expected XMASS detector background [13].

Figure 2. Expected number of supernova burst events at Hyper-Kamiokande for each interaction as a function of the distance to a supernova. The band of each line shows the possible variation due to the assumption of neutrino oscillations [14].
LBNF+DUNE is a long baseline neutrino experiment aiming at the measurement of CP phase and neutrino mass hierarchy using a neutrino beam from Fermilab. 40 kton liquid argon detectors are proposed at the Sanford Underground Research Facility in South Dakota, USA. Among various neutrino interactions on argon, charged-current absorption, $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$ has the largest cross section and it dominates the expected spectrum, so the LBNF+DUNE detector can measure a precise $\nu_e$ spectrum with about 2,300–2,800 events. In addition, about 200–300 electron scattering events and 130–200 $\bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{Cl}^*$ events are expected [15].

Juno and RENO-50 are 20 kton size liquid scintillator detectors for neutrino mass hierarchy measurement using reactor neutrinos. They are single volume detectors with the same concept as KamLAND and Borexino, and a high resolution measurement of $\bar{\nu}_e$ spectrum is expected as well as precise $\nu_X$ temperature measurement.

4. Supernova relic neutrinos
Supernovae have been occurring since the beginning of the universe, and the neutrinos from all the supernovae have been accumulated as diffuse neutrinos in our universe, called supernova relic neutrinos (SRNs). SRNs would tell us the star formation history of the universe. The predicted spectra of SRN [16] are shown in Figure 3. Since reactor neutrinos and atmospheric neutrinos are dominant background below 10 MeV and above 30 MeV respectively, 10–30 MeV is an open window for the SRN measurement. SK has been searching for SRN not only by only detecting prompt positron signals but also by coincidence detection of positrons and delayed 2.2 MeV gammas from protons which captures neutrons; however, it is still constrained by background because the efficiency of the 2.2 MeV detection with Cherenkov lights is low. By adding 0.2% gadolinium sulfate into the 50 kton water tank, this situation should be significantly improved [17] as shown in Figure 4. Gadolinium has a thermal neutron capture cross section of 49,000 barns (about 5 orders of magnitude larger than that of protons) and emits a gamma
Figure 4. Neutron tagging with gadolinium (left), and capture efficiency as a function of Gd concentration (right) [18].

Figure 5. Expected background components of SK-Gd (left), and expected SRN spectra of some models [16] (right).

cascade of 8 MeV that can be easily detected using Cherenkov light. In order to obtain a 90% efficiency for neutron capture, the Gd concentration should be 0.1%, or 0.2% if Gd$_2$(SO$_4$)$_3$ is used, as illustrated in Figure 4. Figure 5 shows expected signal spectra for SRN models and conservative background estimation of atmospheric neutrinos with its component. Table 1 shows the expected number of events and background with 10 years observation. Here, we assume the $\nu_\mu$ CC background events are 1/4 of those of SK, $\nu_e$ CC background events are 2/3, and NC background events are 1/3 with neutron tagging, respectively. Topological information of events should allow to reduce the background further, but it is not included in this estimation.

5. EGADS
In order to study the effect of dissolving Gd in the SK tank, an R&D project called EGADS (Evaluating Gadolinium’s Action on Detector Systems) has been running in the Kamioka mine. A new hall was excavated near SK and a 200 m$^3$ stainless steel tank with ancillary equipment was constructed. The idea is to mimic the SK conditions inside the 200 m$^3$ tank. The tank is equipped with a selective water filtration system that removes impurities while retaining the
Table 1. Expected numbers of SRN signals and backgrounds through SK-Gd 10 years observation

| Model [16]         | 10-16 MeV | 16-28 MeV | Total  | significance |
|--------------------|-----------|-----------|--------|--------------|
| $T_{\text{eff}} = 8\text{ MeV}$ | 11.3      | 19.9      | 31.2   | 5.3$\sigma$  |
| $T_{\text{eff}} = 6\text{ MeV}$ | 11.3      | 13.5      | 24.8   | 4.3$\sigma$  |
| $T_{\text{eff}} = 4\text{ MeV}$ | 7.7       | 4.8       | 12.5   | 2.5$\sigma$  |
| $T_{\text{eff}} = \text{SN1987a}$ | 5.1       | 6.8       | 11.9   | 2.1$\sigma$  |
| BG                 | 10        | 24        | 34     | —            |

Figure 6. Percentage of Cherenkov light remaining for water inside the instrumented 200 m$^3$ EGADS tank for increasing concentrations of gadolinium sulfate. The green, red, and blue lines correspond to data taken from the top, center, and bottom sample points of the 200 m$^3$ tank, respectively, while the light blue band shows the range of ultra-pure water transparencies during SK-III and SK-IV. The inset is the gadolinium sulfate concentration history, as measured by the AAS, for the three sampling points in the top, center and bottom of the EGADS detector [19].

Gd, a 15 m$^3$ Gd premixing and pretreatment plastic tank, and a device to measure the water attenuation length (called UDEAL).

Figure 6 shows the history of the measured water transparency in the 200 m$^3$ tank since October, 2014. The four loadings are clearly identified. It demonstrates that transparencies can be comparable to those achieved at the pure-water SK’s phases III and IV, and that in steady operation the measured transparencies are nicely stable at values very appropriate for physics analyses. The Gd$_2$(SO$_4$)$_3$ concentration in the 200 m$^3$ tank is monitored by using an Atomic Absorption Spectrometer (AAS). Water samples are collected by a pump from three points in the detector, at three different height, using the same pipe as the UDEAL sampling. The measured concentration since November 2014 is also shown in Figure 6. The four loadings are clearly seen as steps in the concentration. The concentrations at all three sampling points are: 1) very close to each other, indicating that there is a homogeneous solution in the 200 m$^3$ tank, and 2) stable between loadings or any other external intervention, demonstrating that there is no significant Gd loss during continuous water recirculation and purification.
6. Implementation in Super-Kamiokande

A T2K+SK joint protocol is being established to take the decision about when to trigger the project and its implementation. It takes into account the needs of both experiments, the readiness of SK-Gd project, the T2K schedule, the J-PARC MR power upgrade and other miscellaneous elements. The current expected time of start is 2018. With respect to the SK detector probably the most critical item is its refurbishment of the tank. The scaling up of EGADS water system for SuperK-Gd is well under way. The current plan for the implementation of SK-Gd has three phases. The first period is for the tank refurbishment, pure water fill, and recirculation of pure water in the detector until good water transparency is achieved. The second period is for loading $\text{Gd}_2(\text{SO}_4)_3$ up to 0.02%, which corresponds to $\sim 50\%$ neutron capture efficiency on Gd. We will run the detector for a while at this concentration in order to study backgrounds and neutron capture efficiency. In the third period we will add the remaining $\text{Gd}_2(\text{SO}_4)_3$ needed to achieve our full target loading, 0.2%.

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