Prospect for detection of neutrinos from supernova explosion

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Abstract

The detection of the neutrino burst from supernova explosion by Kamiokande, IBM, and BAKSAN on the 23rd of February, 1987 opened the door to the new era of neutrino astrophysics. Nowadays, many neutrino detectors are running to detect neutrinos from supernova explosions. On the other hand, the diffuse flux of neutrinos from all past supernovae, supernova relic neutrinos (SRN), exists in space. Since large target mass and high background reduction are necessary, SRN has not been observed. For observation of SRN, GADZOOKS! project has been proposed and R&D project is ongoing.

Keywords: Neutrino, Supernova, GADZOOKS!

1. Supernova Neutrino

A supernova explosion happens for a star with mass more than 8 times that of the sun. Supernova explosion releases gravitational energy of an order of $10^{53}$ erg, and most of it (99%) is carried away by neutrinos. A simulation of time profile of luminosity and average energy of neutrinos are shown in Fig.1. Hence, the detectors are required to have a low energy threshold as low as several MeV. The expected rate of supernova in our galaxy is only a few per century and the burst itself is only about 10 seconds long. So, the supernova detectors should run all the time with minimum loss time.

Super-Kamiokande (SK) is a 50 kton water Cherenkov detector. The dominant interaction is the inverse beta decay (IBD) in supernova neutrino energy range. About 8000 events are expected for a supernova explosion at 10 kpc. It has enough statistics to discuss various theoretical models of the supernova explosion. In addition, SK is able to detect directional information using electron scattering events. A real time program to monitor a supernova burst, called SNWATCh, is always running and it can process data within about 2 minutes for 8000 events. When SNWATCh detects a candidate, alarm e-mails and phone calls are automatically sent to experts so that announcement of the detection can be report to the world within one hour.

IceCube is a ice Cherenkov detector with 5160 PMTs in cubic kilometer size target in clear giant ice at the South Pole. Although it is a detector for high energy neutrinos, IceCube can detect SN bursts as a coincident increase of single count rates of all PMTs. It is able to measure time profile of energy flow with high statistical precision.
KamLAND and Borexino, and SNO+ currently under construction, are large single volume scintillation detectors. The dominant interaction is IBD which is expected few hundred events/kton for 10 kpc supernova. Several tens of NC gamma events with 15.1 MeV \( \gamma \) ray are expected for 10 kpc supernova. Several hundred neutrino proton elastic scattering events/kton \((\nu + p \rightarrow \nu + p)\) are also expected, and it is independent from neutrino oscillations; hence, proton recoil energy spectrum enables us to measure neutrino energy spectrum of high energy component [3].

HALO detector is a dedicated detector for supernova neutrinos, which consists of \(^3\)He counters and 79 tons of Pb target. The detector is mostly sensitive to the \(\nu_e\) charged current interaction on Pb. And they expect \(\sim 40\) events for 10 kpc supernova.

Surface large volume detectors like NO\(\nu\)A, Double Chooz, RENO, and Daya Bay will also be able to extract supernova signals. Some neutrino detectors are connected to the SNEWS system (Supernova Early Warning System) [4], which dispatches a warning signal to registered people if a coincidence of the neutrino detectors is observed.

2. Supernova Relic Neutrino

Supernova is a rare phenomenon, occurring only a few times in a century. In the universe, however, there exist neutrinos released from the past supernova explosions, which is called Supernova Relic Neutrino (SRN). Expected energy spectrum can be seen in Figure 2. The SRN observation would be a key for not only stellar collapse but also cosmology, as it determines the stellar evolution rate. Several detectors have been searching the SRN signal, but it has not been observed yet.

2.1. Gd-doped water Cherenkov detector

Although SK has the best sensitivity to the SRN via IBD [6], search for SRN is limited by background. The project of Gadolinium (Gd) dissolving into the SK pure water has been proposed, which is named GADZOOKS! [7], in order to detect SRN in the world. Gd has the large cross section for thermal neutron and emits the 8 MeV \(\gamma\)-rays cascade. By delayed coincidence detection of prompt position signal and delayed 8 MeV \(\gamma\)-ray cascade signal, IBD induced by SRN can be selected uniquely from the background events.

The ability of identifying anti electron neutrino by IBD will provide the another benefit to SK analysis, e.g. SK will be able to separate the electron scattering and IBD, consequently supernova pointing accuracy is improved to 3 degree from current 5 degree.

2.1.1. EGADS experiment

The dedicated R&D facility for Gd-doped water Cherenkov detector was constructed near SK detector in the Kamioka mine (Figure 3), this R&D is called EGADS [Evaluating Gadolinium Action on Detector System] experiment. EGADS is mainly con-

![Figure 2: The \(\nu_e\) energy spectrum for theoretical SRN model [5], reactor, and atmospheric.](image)

200 ton tank

![Figure 3: The schematic view of the R&D detector for Gd-doped water Cherenkov detector. 240 photosensors were mounted inside the 200 ton tank.](image)
tank. The transparency of water was evaluated with a Cherenkov light left at 15 m (called LL15m hereafter) which takes into account the Cherenkov light spectrum, wavelength dependent attenuation length and the quantum efficiency of PMT. The obtained LL15m value for the 0.2% Gd$_2$(SO$_4$)$_3$ solution was 69%. Compared with the LL15m for pure water (∼82%), LL15m of the Gd-loaded water is 84% of that of the pure water. This almost meets the requirement to do physics in SK detector.

The Gd $\gamma$-ray measurements were done using a neutron source. We adopted a Am/Be source which emits the 4.4 MeV $\gamma$ ray and neutron via: $\alpha + ^9$Be $\rightarrow ^{12}$C$^*$ (4.4 MeV de-excitation $\gamma$ ray )+n using the $\alpha$ from $^{241}$Am. The Am/Be source is on a BGO crystal which emits scintillation light with the 4.4 MeV prompt $\gamma$ ray. So, this setup mimics IBD signal. The energy spectrum of delayed events were observed as shown in Figure 5. Data and MC agree well.

3. Supernova Neutrino from the Si burning state

If a massive star has reached a stage just before supernova, we may get a precursor of the explosion. About a week before the explosion, at the Si-burning phase, anti electron neutrinos are produced via electron-positron annihilations in the core. Although, its neutrino luminosity is eight orders of magnitude smaller than that of the forthcoming collapse, it could be detected if the distance to the star is as short as a few hundred parsec like Betelgeuse. The detection of this precursor is important because it provides us the chance to investigate the evolution of a star at the final stage of collapse and issue the very prompt alarm before the supernova neutrino burst.

The average energy of this pre-supernova neutrinos is smaller than one of the burst. (It is about 1 MeV). The energy of the most of those neutrinos are below the reaction threshold of the IBD but the events at higher energy tail (actually above 1.8 MeV) can be detected by KamLAND as IBD signals. The prompt alarm by pre-supernova can be issued from 3 days to 5 hours before the time of the core collapse.

In current SK, positron signals induced by pre-supernova neutrinos are invisible. In Gd-enhanced SK, however, pre-supernova is observed as gradual increasing of the single rate by the neutron captured Gd $\gamma$ ray. The expected number of neutron interactions are estimated to be ∼796 (∼477) for 24-0 (3-0) hours before the collapse based on the calculation in [8].(note that distance to Betelgeuse is assumed to be 200 pc here).

4. Summary

Supernova offers an unprecedented opportunity for very important information for neutrino astrophysics. Current detectors in the world are waiting for a galactic supernova.

References