PROCEEDINGS OF SCIENCE

Development of the Pre-Supernova Alert System for Super-Kamiokande

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The current phase of the Super-Kamiokande experiment, SK-Gd, is characterized by the addition of gadolinium sulfate to the water Cherenkov detector, which improves the detection capability of thermal neutrons. For low energy events, the main detection channel for electron anti-neutrinos is the inverse beta decay interaction, which has, in its final state, a positron and a neutron. The neutron thermal capture by gadolinium emits gamma-ray cascades with energies about 8 MeV, improving the identification of the products of this process, which reduces the background for low energy events and allows the analysis of neutrinos with energies below the usual Super-Kamiokande thresholds. One possible detection by SK-Gd is the neutrinos coming from massive stars at the last evolutionary stage before core-collapse supernova, known as pre-supernova stars. During this stage, pair annihilation and beta decay processes are the main cooling mechanisms of the stars, emitting high fluxes of electron anti-neutrinos. Their detection could provide an early warning for core-collapse supernovae. The techniques for the development of a supernova alert system for Super-Kamiokande based on the detection of pre-supernova neutrinos and the expected sensitivity are presented.

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1. The Super-Kamiokande Experiment

Super-Kamiokande (SK) is a 50 kton water Cherenkov detector with 22.5 kton fiducial volume located in the Kamioka mine in Japan, overburden with 1000 m of rock. It is a stainless-steel tank with a diameter of 39.3 m and 41.4 m height. The detector is divided in a inner detector containing about 11,100 20-inch photomultiplier tubes (PMTs), with dimensions 33.8 m diameter and 36.2 m height, and an outer detector with a water layer 2 m thick, containing about 1,885 8-inch PMTs, facing the outside of the detector.

SK is a multi-purpose observatory: neutrinos with energies from a few MeV to few hundred of GeV can be detected from different sources, such as the Sun, atmosphere, supernovae, diffuse supernova neutrino background (DSNB), reactors and beams from T2K.

The Super-Kamiokande with Gadolinium (SK-Gd) phase started in July 2020 with the addition of about 13 tons of gadolinium sulfate octohydrate, $Gd_2(SO_4)_3 \cdot 8H_2O$, to the water in the detector, achieving a concentration of 0.01% Gd by mass. The goal of this project is to enhance the identification of neutrons resulting from inverse beta decay (IBD), which is the main interaction channel for low energy $\bar{\nu}_e$. The efficient IBD and neutron detections bring benefits to different analyses in SK such as supernova neutrinos, proton decay and atmospheric neutrino studies, and in the search for neutrinos from DSNB, which have never been observed. Another possible first-time detection of SK-Gd is the neutrinos coming from the Silicon (Si) burning phase of stars close to the core-collapse supernova (CCSN), also known as pre-supernova (preSN) neutrinos.

2. Pre-supernova Neutrinos

The amount neutrino emission increases significantly as a massive star, with $M_{ZAMS} > 8M_\odot$, approaches the end of its life that can potentially culminate in a CCSN. After the star burns most of its hydrogen, the fusion of other elements starts due to high density and temperature. Figure 1 illustrates the characteristic onion shape of massive stars close to the CCSN. From when the carbon burning starts, the star is classified as neutrino-cooled star [1] for its intense neutrino emission, which can reach a neutrino luminosity of about $10^{12} L_\odot$, while its photon luminosity is only $10^5 L_\odot$ [2]. The electron-positron annihilation process generating thermal neutrinos, $e^+e^- \longrightarrow \bar{\nu}\nu$, becomes the star's dominant form of cooling, producing all flavours of neutrino and anti-neutrino pairs.

The last stage of these stars before the CCSN is the Si-burning, in which the emitted neutrinos have an average energy of 1.85 MeV. At this stage stars are commonly known as pre-supernova (preSN) stars.

Table 1: Approximate duration of burning stages for a 20 $M_\odot$ star and the fraction and average energy of electron neutrinos emitted by pair-annihilation [4].

Burning Stage	Duration	ν_e ($\bar{\nu}_e$) fraction	Average ν energy
C	300 years	42.5%	0.71 MeV
Ne	140 days	39.8%	0.99 MeV
O	180 days	38.9%	1.13 MeV
Si	2 days	36.3%	1.85 MeV

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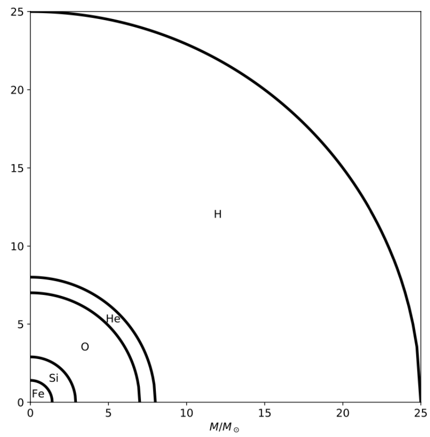

Figure 1: Characteristic onion-shape of a massive star just before the CCSN, where the shells show the abundance of each element. Reproduced from [3].

About 1/3 of the produced anti-neutrino flux in preSN stars is of electron anti-neutrinos, which detection in SK is enhanced with SK-Gd. For the preSN long timescale compared to a supernova, it is possible the creation of an alternative supernova alarm for SK. To estimate the sensitivity in SK, two models for the thermodynamics of stellar evolution are used: Odrzywolek and Heger [4] and Patton et al. [5]. Both models provide online data sets for the calculation of anti-neutrino emission during the preSN stage.

3. Sensitivity to pre-supernova neutrinos

The sensitivity to preSN neutrinos at SK with 0.01% Gd was evaluated using Monte Carlo and SK data to calculate the contributions from different background sources, which later were compared to SK-Gd data. The main backgrounds are:

- Accidental coincidences, which is an intrinsic background of the detector, coming from radioactive decays, dark noise and uncorrelated events that are close in time and distance.
- Radioactive contamination with the gadolinium loading, in which radioactive impurities were distributed in the detector and they contribute to backgrounds from (α, n) and spontaneous fission processes.
- Reactor and geoneutrinos electron anti-neutrinos in the same energy region as preSN neutrinos.
- Spallation, due to cosmic rays muons.

IBD interactions have on their final state a prompt positron and a delayed neutron. The selection of IBD events from preSN is performed by using the time between the prompt and delayed candidates, dT, as well as the distance between their reconstructed positions, dR. Boosted Decision Tree (BDT) techniques are also necessary to improve the expected sensitivity to preSN neutrinos.

Figure 2 shows the evolution of the expected number of IBD events in SK-Gd with 0.01% Gd after cuts for different preSN models for stars 200 parsecs away for both normal and inverted neutrino mass hierarchy. Results also show that in SK with 0.01% Gd can observe preSN neutrinos with a 3σ detection for stars up to 600 parsecs.

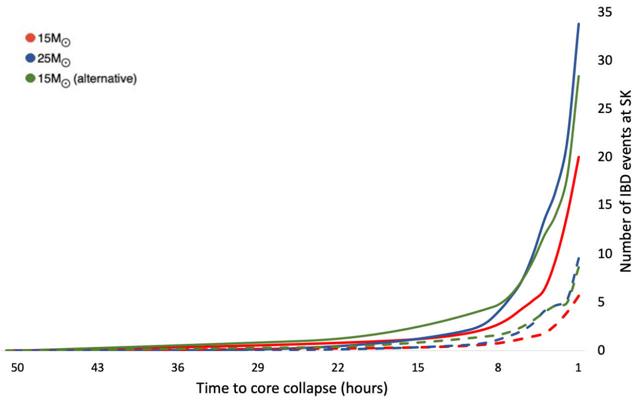

Figure 2: Evolution of the number of IBD events at Super-Kamiokande with 0.01% Gd as a massive star (d = 200pc) approaches the CCSN. Solid lines show normal neutrino mass hierarchy and dashed lines show inverted neutrino mass hierarchy. The considered fluxes are evaluated for stars with $15M_\odot$ and $25M_\odot$ (Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611). An alternative model (Patton, et al 2017 ApJ 851 6) is shown for $15M_\odot$ stars.

4. Pre-Supernova Alert System

A supernova alarm was created for SK looking for preSN neutrino events in real time, sending alerts in case of a potential CCSN. The alarm processes data right after their acquisition in SK, sorting the candidates for IBD events by the absolute time the event happened.

The alert system is integrated to the wide-band intelligent trigger (WIT) system, which is a system designed to increase the sensitivity of SK to very low energy events using a great amount of parallel computing [6]. The alert system receives constantly sub-sets of events from WIT, which go through reduction and the number of candidate events selected from the sub-set is saved. All the selected events inside a specific time-window is accounted and the system performs a statistical evaluation to give an alarm decision, which takes into consideration many factors such as background levels, false positive rates, current detector status, and expected sensitivities. If the decision is positive, the system sends alerts to the possibility of a supernova. The preSN alert system has been operational in SK since October 22^{nd}, 2021.

The expected warning hours as function of distance for a 3σ detection by SK-Gd with 0.01% Gd for which the system would alert to a potential supernova is shown in Figure 3. In the most optimistic scenario, in which Betelgeuse has $15M_\odot$ at a distance of 150 parsecs, with normal ordering neutrino mass hierarchy and following the model from Patton, et al 2017 ApJ 851 6, the alert would be about 9 hours before the CCSN.

For the future phases of SK-Gd with increased concentration of gadolinium, studies are being performed to estimate the sensitivities. Preliminary results showed that Beteulgeuse can get early warnings up to 12 hours and detection ranges extended to over 700 parsecs.

5. Conclusion

Super-Kamiokande is a neutrino observatory running since 1996 and it has recently moved to the SK-Gd phase, achieving a concentration of 0.01% Gd by mass, which will allow SK-Gd

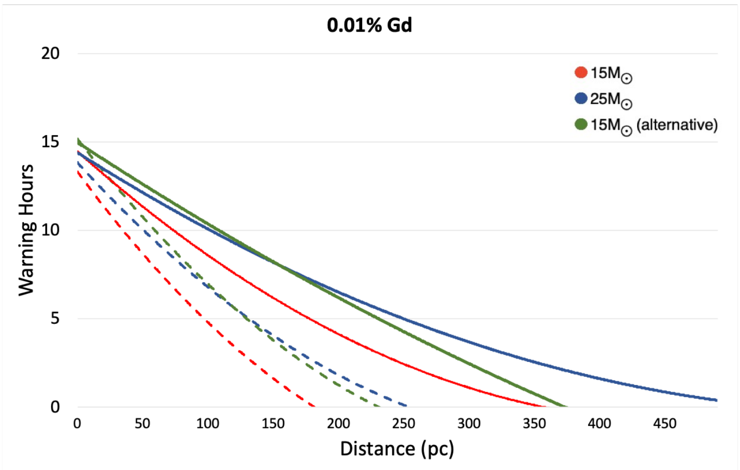

Figure 3: Expected warning hours as function of distance for a 3σ detection by the pre-supernova alert system for Super-Kamiokande with 0.01% Gd. Solid lines show normal neutrino mass hierarchy and dashed lines show inverted neutrino mass hierarchy. The considered fluxes are evaluated for stars with $15M_\odot$ and $25M_\odot$ (Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611). An alternative model (Patton, et al 2017 ApJ 851 6) is shown for $15M_\odot$ stars.

to observe neutrinos never seen before from different astronomical sources such as DSNB and pre-supernova stars.

Pre-supernova $\bar{\nu}_e$ detection can, not only be a powerful observation of interior of stars that propagates maintaining characteristics of the star's core, but also bring evidences for neutrino mass hierarchy. Its potential detection also opened the possibility of developing an alternative supernova alert system for Super-Kamiokande. The system has been running since October 22^{nd} and can give alerts for preSN candidates a few hours before a core-collapse supernova. Beteugelse for instance has an expected optimistic early warning of 9 hours.

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