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Development of analysis method for late-phase neutrino emission from the supernova in Super-Kamiokande

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A new analysis method for supernova model identification using supernova neutrino observations in Super-Kamiokande (SK) is developed. This new method uses information on late-phase neutrinos observed in SK, such as the duration of supernova neutrino and average neutrino energy. In this paper, we report the evaluation results of the supernova identification performance, demonstrating 90% or more in identification performance.

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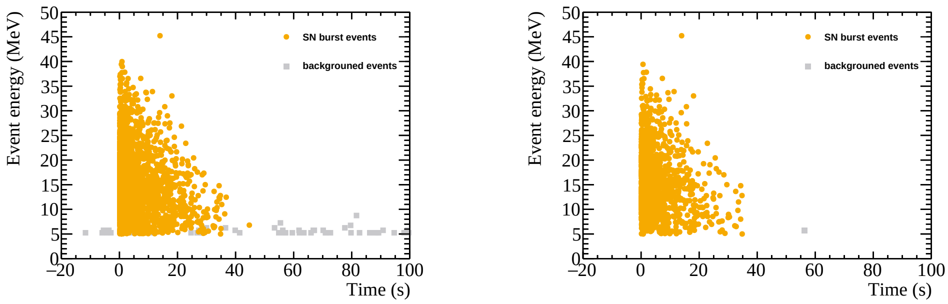
1. Introduction

Core-collapse supernova explosions begin with the collapse of massive stars with masses larger than $8M_\odot$. A large amount of neutrinos is emitted during the explosion. The neutrino burst from a supernova was observed only once in 1987, and 24 events were totally observed in Kamiokande, IMB, and Baksan. If a supernova explosion occurs in our galaxy in the next time, SK is expected to observe 1,000 to 10,000 neutrino events. After the explosion, a remnant called a proto-neutron star (PNS) forms at the center of the supernova. The PNS cools down to become a cold neutron star through neutrino emission, and this phase is referred to as the cooling phase. The neutrinos emitted in this phase are mainly dependent on the mass and radius of the PNS and are, therefore, less uncertain than the early phase of the explosion. In addition, this phase is expected to last for several tens of seconds; a long-term simulation that considers the cooling phase is necessary. However, since the neutrino luminosity in the cooling phase is more than an order of magnitude lower than in the initial phase, an analysis method unique to the cooling phase must be developed. The analysis method focused on this late-phase neutrino has also been studied [1][2].

Figure 1 shows an example scatter plot of observable particle energy in SK as a function of time for a Monte Carlo (MC) simulation. It is assumed that events are observed in full volume (32.5 kton) and fiducial volume (22.5 kton) of inner detector, excluding the distance up to 2 m from the wall applied spallation cut in SK. The circle points represent a signal, and the square points represent a background when the energy threshold is 5 MeV. These signal events are for the model with the Shen equation of state (EOS) and $1.40M_\odot$ PNS mass in Ref.[2]. When searching for supernova neutrinos, the main background in SK is radioactive isotopes produced by the nuclear spallation of oxygen in water caused by penetrating cosmic ray muons, impurities in the detector material, and rocks outside the tank. Spallation events are spatially and temporally correlated with the trajectory of muon track. Therefore, searching for correlations between preceding muons and radioisotope events is the basis of the "spallation cut" in SK, which can reduce about 90% of spallation events. On the other hand, this spallation cut also reduces 20% of supernova neutrino events [3].



Full volume   Fiducial volume

Figure 1: An example scatter plot of observable particle energy in SK as a function of time for a single simulation. The circle points indicate a signal and square points indicate a background. In panels (a) and (b), observations with full and fiducial volumes are assumed, respectively. In (b), much of the background is removed by spallation cut.

2. Method

It is important to get information about the supernova, such as mass and radius of the neutron star, from supernova neutrino events. Therefore, we develop a new supernova model identification method using the number of events (N), average energy (E), and duration of a supernova neutrino event cluster (T_{last}). Here, N includes supernova neutrino and background events, and E means the average energy of charged particles observed in SK.

Determining T_{last} is challenging due to the presence of background events in the supernova neutrino energy regions. Consequently, we have developed a calculation method for T_{last} using appropriate energy threshold (E_{th}) and timing window (T_{wid}). Figure 2 shows a schematic diagram of how T_{last} is determined. The time (T) is measured from the first supernova neutrino event observed in SK as $T = 0$. For $T \geq 0$, we define T_{last} as the smallest value of T that satisfies the condition of having no events above E_{th} within the interval $(T,\ T + T_{\text{wid}}]$. Here, we set $E_{\text{th}} = 8$ MeV and $T_{\text{wid}} = 5$ s to exclude background events within the time span T_{wid} above 5σ. Then, we calculate N and E, respectively, as the event number and the average energy of the events in $0 \leq T \leq T_{\text{last}}$.

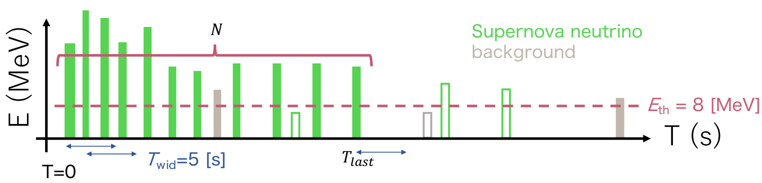


Figure 2: Schematic diagram of determination method of T_{last}.

For the performance evaluation of the model identification, we use 16 supernova models with four EOSs (Shen, LS220, Togashi, and T+S EOSs) and four PNS masses ($1.40M_{\odot}$, $1.47M_{\odot}$, $1.54M_{\odot}$, and $1.62M_{\odot}$) in Ref [2]. T+S EOS is a model that combines Togashi EOS for the higher-density and Shen EOS for lower-density region.

Here, we show the method of the model identification. First of all, we perform 10,000 times MC simulation for each supernova model and make each probability density function (PDF) of N, E, and T_{last}. As a next step, we perform a MC simulation for a designated supernova model, which is denoted as "input model", and obtain N, E, and T_{last}. For obtained N, E, and T_{last}, we calculate P_N, P_E, and P_T, respectively, using the PDFs for each supernova model. We select the supernova model that maximizes the log-likelihood calculated as

$$L = \log(P_T \times P_N \times P_E), \tag{1}$$

and we denote it as a "selected model". The identification is successful if the "selected model" matches the "input model". We assess the success ratio by repeating the model identification process 1,000 times for each supernova model, designating each one as the "input model".

3. Result

Figure 3 shows the model identification performance estimated using 16 models. The horizontal axis represents the "input model", and the vertical represents the "selected model" determined through the log-likelihood calculation. The color of each square shows the ratio of model selection. The diagonal components represent successful identification, demonstrating the performance of over 90% for all models. Conversely, misidentifications are more likely to occur among different mass models with the same EOS or among different EOS models with the same mass. In particular, misidentifications with different mass models are more likely for the models with the Shen EOS because the similarity in T_{last} across different mass models is more than that among other EOS models. However, this method has high identification performance, even considering the above. In actual observations, this analysis is expected to be used in identifying candidates for the EOS, and then a more detailed analysis can be performed.

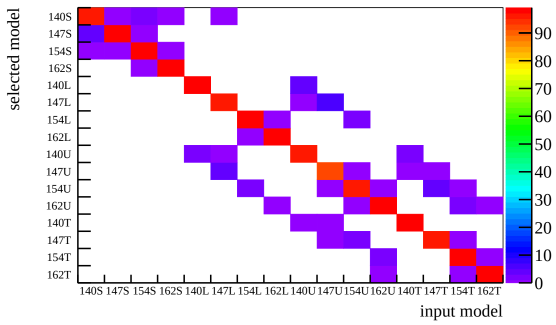


Figure 3: The matrix depicting the ratio of model selection. The horizontal and vertical axes represent the "input model" and "selected model", respectively.

4. Conclusion

Supernova neutrinos provide information on the physical conditions responsible for neutron star formation and the supernova explosion mechanism. In this study, we develop an analysis method for supernova model identification by neutrino observation in SK. Here, we focus on the cooling phase of PNS because the phenomena in this phase are simple. When SK observes supernova neutrinos, we use duration, energy, and the number of events in model identification analysis. It is concluded that 90% or more of the identification performance is achieved.

References

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[3] Super-Kamiokande collaboration, *Solar neutrino measurements in super-kamiokande-iv*, *Phys. Rev. D* **94** (2016) 052010.