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Design, characterization, and sensitivity of the supernova trigger system at Daya Bay

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ABSTRACT

Providing an early warning of galactic supernova explosions from neutrino signals is important in studying supernova dynamics and neutrino physics. A dedicated supernova trigger system has been designed and installed in the data acquisition system at Daya Bay and integrated into the worldwide Supernova Early Warning System (SNEWS). Daya Bay's unique feature of eight identically-designed detectors deployed in three separate experimental halls makes the trigger system naturally robust against cosmogenic backgrounds, enabling a prompt analysis of online triggers and a tight control of the false-alert rate. The trigger system is estimated to be fully sensitive to 1987A-type supernova bursts throughout most of the Milky Way. The significant gain in sensitivity of the eight-detector configuration over a mass-equivalent single detector is also estimated. The experience of this online trigger system is applicable to future projects with spatially distributed detectors.

1. Introduction

About two dozen supernova (SN) burst neutrinos were observed in the Kamiokande II, IMB, and Baksan experiments from stellar collapse SN 1987A when the star Sanduleak-69202 exploded in the Large Magellanic Cloud, about 50 kpc away from the Earth [1–6]. Besides the Sun, SN 1987A remains the only known astrophysical neutrino source that has provided a large range of physical limits on neutrinos as well as the core-collapse supernova mechanism [7–10]. Almost all of the gravitational binding energy of a stellar collapse is carried away by neutrinos and core-collapse supernovae are likely strong galactic sources of gravitational waves. Observations of both neutrinos and gravitational waves could provide deep insight into the core collapse of supernova explosions as well as other fundamental physics [11].

Galactic SN explosions are rare, occurring with a rate of only a few per century [12], so detecting neutrinos from a nearby SN is a once-in-a-lifetime opportunity. SN neutrinos are expected to arrive at the Earth a few hours before the visual SN explosion, which enables an early warning for a SN observation [7]. The Supernova Early Warning System (SNEWS) [13,14] collaborates with experiments sensitive to core collapse SN neutrinos, to provide the astronomical community with a very high-confidence early warning of a SN occurrence, pointing more powerful telescopes or facilities to the event.

The antineutrino detectors (ADs) of the Daya Bay experiment are designed to detect $\bar{\nu}_e$'s via the inverse beta-decay (IBD) interaction $\bar{\nu}_e + p \rightarrow e^+ + n$, with the primary goal of making a precision measurement the neutrino mixing angle θ_{13} [15–19]. Each AD contains about 21.6 tons of liquid scintillator (LS) and 19.9 tons of liquid scintillator doped with gadolinium (Gd-LS), giving a total active target mass of $\sim$ 330 tons in 8 ADs. The water shields (about 2.3 kton in total) around the ADs collect too little light to efficiently detect SN burst neutrinos. A dedicated online supernova trigger system was installed in August 2013 and Daya Bay joined SNEWS in November 2014.

The experiments currently in SNEWS are Super-K, LVD, IceCube, Borexino, KamLAND, and Daya Bay [13]. Though SN burst neutrinos come in all flavors in the few-tens-of-MeV range, the interaction rates in these experiments are dominated by IBD events [20]. Some main features [20,21] of the experiments are summarized in Table 1.

Super-K is the only experiment with pointing capability, which is realized with neutrino-electron scattering interactions and thus applies to only a few percent of the total number of interactions [22]. IceCube can detect a flux of MeV neutrinos via a collective increase in the rates of all PMTs caused by the Cherenkov light produced by the IBD positrons [23]. It cannot distinguish among neutrino flavors nor measure positron energy, although for a galactic SN, it can track the subtle features in the temporal development of the SN neutrino bursts [24]. KamLAND, Borexino, and Daya Bay have finer energy resolutions (e.g. $\sigma_E/E \approx 3\%$ at 10 MeV for Daya Bay) and lower energy thresholds (below the IBD reaction threshold of 1.8 MeV), which provide sensitivity to the full spectrum of the SN burst electron-antineutrinos.

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Table 1
Supernova neutrino detectors in SNEWS and their capabilities. N_{IBD} is the expected number of IBD events from a SN at 10 kpc, with an emission of 5×10^{52} erg in $\bar{\nu}_e$'s, and an average $\bar{\nu}_e$ energy around 12 MeV, which is compatible with SN 1987A measurements.

Detector	Type	Location	Mass (kt)	N_{IBD}	E_{th} (MeV)
IceCube	[a]L.S. Ch.	Antarctic	0.6/PMT	N/A	–
Super-K	Water Ch.	Japan	32	7000	7.0
LVD	Scint.	Italy	1	300	4.0
KamLAND	Scint.	Japan	1	300	0.35
Borexino	Scint.	Italy	0.3	100	0.2
Daya Bay	[b]M.S. Scint.	China	0.33	110	0.7

[a] Long-string Cherenkov.
[b] Multiple-site scintillator.

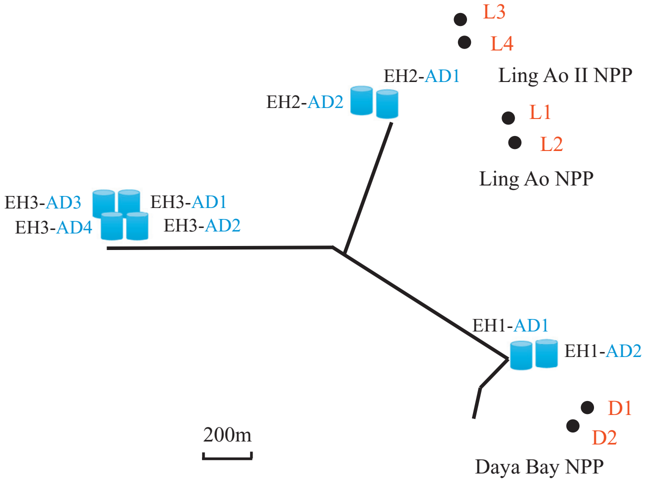

Fig. 1. Layout of the Daya Bay detectors. The dots represent reactor cores, labeled as D1, D2, L1, L2, L3 and L4. The black line represents horizontal tunnels that connect three underground experimental halls (EHs), where 8 ADs are installed.

Daya Bay has a unique feature of 8 identically-designed detectors deployed in three separate experimental halls (EHs, Fig. 1), which are >1 km apart from each other and whose maximum overburdens in equivalent meters of water are 250, 265, and 860, respectively. The online supernova trigger system at Daya Bay can provide an alert to the experiment and to SNEWS within 10 s, since the impact from muon-induced and accidental backgrounds or abnormal noise occurring in a single-detector is minimized by the separation of detectors. Daya Bay has the prominent features of a prompt alert and well controlled false-alert rate.

2. Overview of the online supernova trigger system

An overview of the online supernova trigger system of Daya Bay is shown in Fig. 2. The system is composed of three sub-systems: online, offline, and monitoring.

IBD events are reconstructed and selected (see Section 3.1) in the online sub-system which contains software applications embedded in the Event Flow Distributer (EFD, Appendix A) of the Data Acquisition (DAQ) system [25]. An IBD selection program for each AD accesses the raw data and provides the information of selected IBD candidates to an Information Sharing (IS, Appendix A) server. The IS server caches the IBD candidates from each AD to a 2-min buffer and combines them every second to form an online supernova trigger candidate based on the previous 10-s window (see Section 3.2). Then, the online supernova trigger candidates are delivered to the offline sub-system via a Distributed Information Management (DIM, Appendix A) system, where they are compared against the trigger threshold.

The offline sub-system processes the input from the online sub-system with several standalone programs running in an onsite farm. Supernova candidate triggers are categorized as golden triggers (1 per 3 months) or silent triggers (1 per month). Both types are written into a database and generate an email alert to Daya Bay collaborators. The datagram is then sent to SNEWS. An offline cross check will be performed to confirm or retract the triggers. The datagram sent to SNEWS includes the experiment title, the alert date and time, the trigger duration, the number of neutrino signals and the type of the trigger.

Based on the existing DIM Name Server (DNS, Appendix A) in the Daya Bay Detector Control System (DCS) environment [26], a real-time monitoring program located in the onsite farm communicates with the existing DAQ and the online and offline sub-systems of the supernova trigger system via DIM to obtain the trigger system status and trigger information. There is a 1 Hz heartbeat to the IBD selection program from the IS server. If the 8 ADs are not running simultaneously outside a tolerance of 2 min, a warning will be sent and the trigger system will continue to operate with the active ADs. Any abnormal running status for any level of the online supernova trigger system automatically generates an error report and mails it to experts. Real-time data is recorded, including the working hours of the online supernova trigger system, each AD's IBD candidate rate, unsolved errors, number of supernova triggers, and the network connection status to SNEWS. An automated daily report is sent to the supernova trigger working group, serving as a daily check of the online supernova trigger system.

3. Algorithm of the online trigger

This section describes the online algorithm, which searches for a simultaneous increase in IBD rate in all ADs within a 10-s window. First, the IBD event selection is introduced, followed by the supernova trigger algorithm and the packing of consecutive supernova triggers. Lastly, the resulting detection probability is presented.

3.1. IBD event selection

3.1.1. Event time, energy and vertex

In order to achieve a *prompt* (fast) online supernova trigger, it was necessary for the event reconstruction to attain a balance between simplicity and effectiveness. The IBD prompt signal trigger time is identified as the time of the IBD event. Trigger times are provided by the GPS, which deviates from UTC time within 200 ns. Energy is reconstructed using an average PMT gain and an average energy scale (photoelectron yield per unit of deposited energy in the liquid scintillator) from calibration:

$$E = \frac{\text{ADC Sum}}{[\text{Average PMT Gain}] \cdot [\text{Average Energy Scale}]}, \tag{1}$$

where 'ADC Sum' is the sum of ADC values with baselines subtracted for all PMT channels. The variation of the product of 'Average PMT Gain' and 'Average Energy Scale' calibration constants is less than 1% per year. The ADC values are provided by the front-end electronics (FEE) [27], which integrate each PMT signal. A charge-weighted method involving the PMT charges and PMT locations is utilized for a rapid vertex reconstruction, i.e.

$$\mathbf{X} = \frac{\sum_{\mathrm{PMT}} \mathrm{ADC}_{\mathrm{PMT}} \cdot \mathbf{X}_{\mathrm{PMT}}}{\sum_{\mathrm{PMT}} \mathrm{ADC}_{\mathrm{PMT}}}. \tag{2}$$

The online reconstruction is sufficiently effective for online supernova triggering, though it cannot reach the same performance as the offline analysis reconstruction.

3.1.2. IBD signal selection and background sources

Daya Bay ADs identify SN $\bar{\nu}_e$'s via the IBD reaction chain $\bar{\nu}_e + p \to e^+ + n,\ n + \mathrm{H/Gd} \to \mathrm{D/Gd} + \gamma/\gamma'$s. The IBD selection basically