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Supernova Neutrino Detection with LHAASO-MD

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The core-collapse supernova releases a tremendous number of neutrinos, which can provide insight into many research areas, including particle physics, astrophysics, nuclear physics, and cosmology. We can detect the signal through a positron produced from the inverse beta decay (IBD) interaction between the electron antineutrino and water. The Large High Altitude Air Shower Observatory[1] muon detector (LHAASO-MD) with 51-kton water can serve this purpose. The MD detectors have been designed to have a scattered layout as well as spatial uniformity. We hope to design a dedicated supernova trigger system in the data acquisition system to take advantage of these unique detector characteristics. The large numbers of MeV-scale supernova burst neutrinos can be observed from a collective rise in all photomultiplier rates on top of the dark noise. This system should effectively suppress the cosmic ray background, optimizes the neutrino detection sensitivity, and realizes the supernova neutrino detection by optimizing the online trigger, data acquisition, and offline data analysis at LHAASO. The trigger system is estimated to be fully sensitive to 1987A-type supernova bursts throughout most of the Milky Way and can eventually help LHAASO join the SuperNova Early Warning System (SNEWS).

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1. Introduction

On February 24, 1987, a neutrino burst, which signified the event as a type II core-collapse supernova in the case of SN 1987A in the Large Magellanic Cloud at a distance of roughly 50 kpc, was retrospectively detected by several detectors ([2]). SN1987A provides a unique opportunity to observe the neutrino emission from a supernova. Besides the Sun, SN1987A remains the only known one to be detected by its neutrino emissions, which could provide a large range of physical limits on neutrinos as well as the core-collapse supernova mechanism. A total of 24 neutrino events in the Kamiokande[3], IMB[4], and Baksan[5] underground experiments were recorded over a time interval of about 12 seconds. About half of the events came in the first second. Most of the events came in the first two seconds. Their individual energies range are from 10 MeV to 50 MeV, which refers to the energy of secondary positrons produced by the captures of such neutrinos on protons.

Supernova neutrino burst event is rare. The burst occurs at the rate of only a few per century [6]. The detection of the neutrino burst from the next galactic supernova can provide an early warning for astronomers. The Supernova Early Warning System (SNEWS[7]) is to provide a World-wide alert of the supernova neutrino signal. SNEWS could also serve as a trigger for those experiments, which not able to be triggered by supernova signals by themselves. Extra interesting data could be saved in this case.

2. Design of LHAASO-MD

The Large High Altitude Air Shower Observatory (LHAASO[8]) is a new generation experiment, which includes 1171 muon detectors (MDs) for measuring the number density and the arrival time of extensive air shower (EAS) secondary muons. The MDs are in a triangular grid with a spacing of 30m in the central part of the array, which has a scattered layout and spatial uniformity. The design with a water Cherenkov detector underneath the soil is chosen for MDs. For each MD unit, a water bag with a diameter of 6.8m and a depth of 1.2m is used to enclose pure water. The liner reflectivity for the water bag is better than 95%, and the water absorption length is designed to be longer than 50 m. There is a 2.5m thickness of the overburdened soil over the MD water bag. An 8-inch PMT sits at the top center of the water bag and looks downward through a highly transparent window into the water. For each MD unit, there are 0.044 kton water and a total of 51 kton water for all 1171 MD units, which could provide a huge target for neutrino detection. Each MD has a detection efficiency better than 95%.

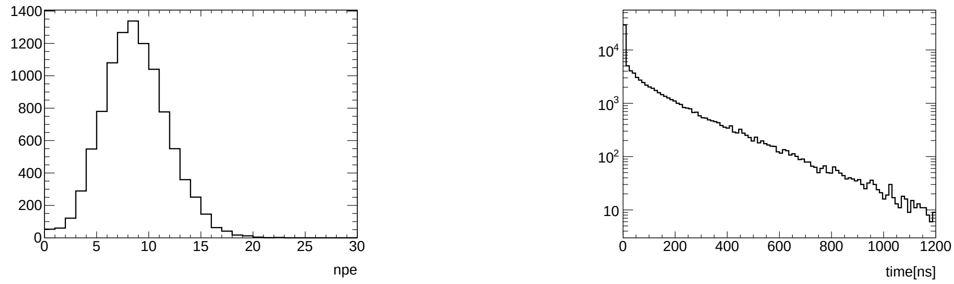
Supernova neutrino is detected by the inverse beta process(IBD) in most experiments. IBD process describes a neutrino scattering off a proton and producing a neutron and positron

$$IBDprocess : \nu_e + p \rightarrow n + e^+.$$

In this process, positron carries almost all the energy from the neutrino. The neutrino detection experiments can be divided into two categories. The first category experiments could do the IBD event reconstruction. In this case, those background events can be suppressed effectively while usually, the target mass is small. The second category experiments could only see the collective rise in all events rates on top of the dark noise. In this category, there are many background events while the target mass is huge. LHAASO-MD is the second one. Huge target mass means more IBD Events. The comparison between LHAASO-MD and other experiments could be found in Table 1.

Detection method	Experiment	Target	Target mass (kton)	IBD Events	Threshold (MeV)	Material coverage	Number and distance of detector units	background rate(Hz)
1st IBD Event Reconstruction	KamLAND	Liquid scintillator	1	300	0.35	underground 1000m	single	<1
	LVD	Liquid scintillator	1	300	4	underground 1400m	single	<1
	Borexino	Liquid scintillator	0.3	100	0.2	underground 1400m	single	<1
	Daya Bay	Liquid scintillator	0.33	110	0.7	underground 250-860m	8	<1
	JUNO	Liquid scintillator	20	6700	0.5	underground 700m	single	<1
	Super-K	water	32	7000	7	underground 1000m	single	<1
2nd Collective rise in all events rates	IceCube	Ice	1000	134000	-	under ice 1450-2450m	5160DOMs, 7,72/42m	540->286
	LHAASO-WCDA	water	300	20000	-	on the ground	3120, Close to each other	>30K
	LHAASO-MD	water	51	12750	5	underground 2.5m	1171, 30m	8k->400?

Table 1: Compare of LHAASO-MD with other experiments.



(a) Distribution of Photoelectron Number

(b) Photoelectron arrival time for 10000 positron events. Time 0 is the positron injection time

Figure 1: The Monte Carlo simulation for 20 MeV positron

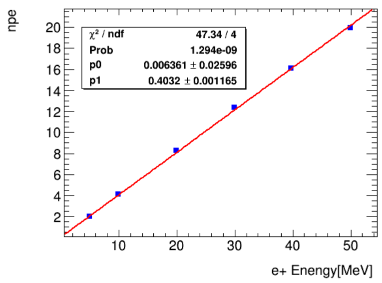


Figure 2: number of photoelectrons versus positron energy

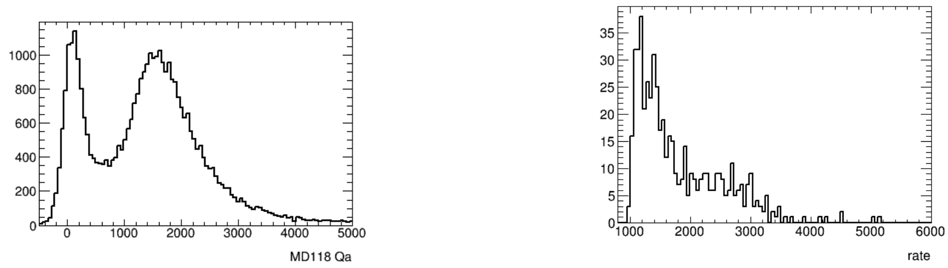
3. MD simulation and Detector performance

10000 positrons are simulated and injected into MD detectors at different positions at energies of 5, 10, 20, 30, 40, and 50 MeV by Geant4_10.4.2[9]. In Figure 1, the left plot shows the distribution of photoelectron numbers for 20 MeV positrons. On average 8 photoelectrons will be collected for 20MeV positrons. The right plot shows the arrival time of the photoelectrons for 20MeV events. 97.2% of the photoelectrons arrive in 608 ns. In the plot time t = 0 indicates the positron injection time. Figure 2 is the simulated number of photoelectrons versus positron energy. Photoelectron number increases with the positron energy. The figure could be fitted by:

$$N_{Photoelectron} = 0.4 \times E_{Positron}$$

Here $N_{Photoelectron}$ denotes the expected photoelectron number from positron and $E_{Positron}$ is the injected positron energy. For 10MeV to 50 MeV positrons from supernova neutrino, LHAASO-MD could receive 4 to 20 photoelectrons in hundreds of ns.

A special trigger mode with all MD hits recorded was tested on Sep 18, 2019, at LHAASO-MD. From those full recorded data, the single MD data acquisition rate is about 8000 Hz. In Figure 3 the left plot is the read-out signal from a single MD. The first peak is the noise from electronics and other random sources, and the second one is from muon events. As the positron from neutrino events should be in the energy range from 10-50MeV[2]. Most noise and muon signals could be reduced by energy cut 10-100MeV(100-1000ADC counts). The right plot of Figure 3 shows the



(a) Distribution of MD Qa (b) Distribution of MD rate

Figure 3: Distribution of MD Qa and rate

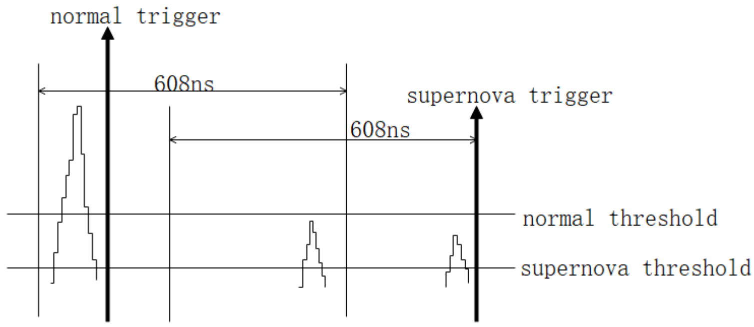


Figure 4: New trigger design for supernova neutrino

mean hits rate of 500 MDs between 100-1000ADC count. The average MD data rate is about 2000 Hz after the energy cut.

4. FPGA programming

For each MD, about 4-20 photoelectrons arriving in hundreds of ns for supernova neutrino signal. Normally there will be only about 1-2 photoelectrons arriving at the same time. The LHAASO normal MD threshold is 1.7 pe, which means at least two photoelectrons arriving in 2 ns will be triggered efficiently by the current setting. The trigger efficiency for neutrino from the supernova is low. A new trigger design is needed to trigger 4-20 photoelectrons in hundreds of ns.

The FPGA Level trigger programming with the sliding windows method is on progressing to trigger the neutrino events. This supernova trigger mode can be updated through the FPGA firmware in the MD electronics. The major idea of trigger designing is to find the neutrino events in the sliding windows of width 608ns. As Figure 4 shows, if many small signals in the sliding window exceed the supernova threshold, a supernova trigger will be sent out. The number of the small signals can be configured. This trigger mode will not affect the normal trigger mode as Figure 5.

We hope this FPGA programming work could be done soon.

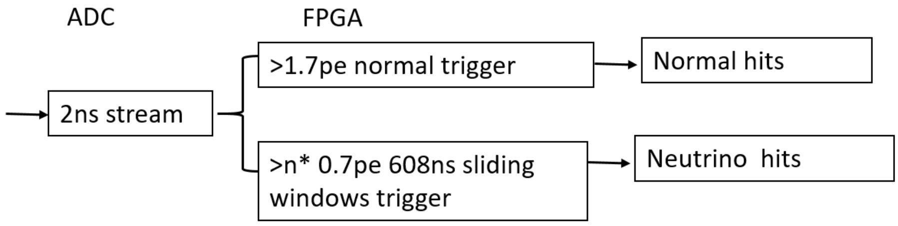


Figure 5: New trigger mode

5. Significance estimation

Counting N_i pulses during a given time interval Δt, rates $r_i = N_i/\Delta t$ for MD i, are derived. The index i ranges from 1 to the total number of MD. r_i is rate expectation values approximated by Gaussian distributions, and $< \sigma_i >$ is the corresponding standard deviation expectation values. The time windows exclude 30 s before and after the investigated bin to reduce the impact of a wide signal on the mean rates.

The most likely collective rate deviation $\Delta\mu$ of all single MD noise rates r_i from their individual $< r_i >$ values, is obtained by maximizing the likelihood

$$\mathcal{L}(\Delta\mu) = \prod_{i=1}^{N_{MD}} \frac{1}{\sqrt{2\pi} < \sigma_i >} exp(-\frac{(r_i - (< r_i > + \epsilon_i \Delta\mu))^2}{2 < \sigma_i >^2}$$

Here ϵ_i denotes a correction for MD_i and detection probabilities.

From the calculation from Super-K experiment[10], LHAASO-MD could have 12750 IBD events within 10 seconds if a nearby supernova bursts. For the first second, each MD unit could have 12750/2/1171=5 IBD events. Now the average noise rate is about 2000Hz. Significance for 1171 MDs:

$$\sqrt{1171} \times 5 \div \sqrt{2000} = 3.5\sigma \tag{1}$$

To get a better significance, it is important to lower the noise level using different methods. The noise from electronics and other random sources could be suppressed by FPGA programming. Those Muon events could be reduced by muon template fit.

6. Conclusions

We hope to design a dedicated trigger system in the data acquisition system as a supernova neutrino trigger with LHAASO-MD. Now an FPGA Level programming is needed to trigger the low energy signals. We hope LHAASO could be a member experiment of SNEWS in the future.

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