A wide-band solar neutrino trigger for Super-Kamiokande

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DOI: 10.7529/ICRC2011/V04/0723

Abstract: Super-Kamiokande observes the elastic scattering of ^{8}B solar neutrinos on electrons. At present the recoil electron energy analysis threshold is 5 MeV. The first step to data analysis below 5 MeV is a lower trigger threshold. An observation of a solar neutrino signal at 4 MeV would open up the transition region between vacuum and matter oscillation. The new DAQ electronics installed in September 2008 enables the readout of every single hit using a software trigger rather than a hardware trigger. However, the trigger threshold is currently not significantly reduced. A new trigger system, the Wideband Intelligent Trigger (WIT), simultaneously triggers and reconstructs very low energy electrons. The current WIT system comprises 8 quad-core CPUs and is specifically designed to trigger with close to 100% efficiency on electrons above 4 MeV. Plans for a more powerful WIT system that can reach Super-Kamiokande's event reconstruction limit of 3 MeV are also presented.

Keywords: Super-Kamiokande, ^{8}B solar neutrinos, WIT

1 Introduction

Super-Kamiokande (SK) [1] is a water Cherenkov detector for neutrino physics and proton-decay search and is located underground at a depth of 1000 m in Kamioka Township, Japan. The detector consists of a stainless steel tank containing 50000 tons of pure water that houses an inward-facing array of about 11000 20" photomultipliers (PMTs) and an outward-facing array of about 2000 8" PMTs. The fraction of surface area covered by the 20" PMT photo-cathode is 40%. About six photo-electrons from Cherenkov light per MeV are observed.

Below about 100 MeV most PMT signals are due to single photon 'hits', i.e. PMT's struck by one Cherenkov photon. For such hits, the resolution of the hit arrival time is about 3 ns. Due to the large size of SK, it takes Cherenkov photons up to 220 ns to traverse the detector, and the relative PMT hit times can be used to reconstruct the point of origin (event vertex) of the light. The signal is due to Cherenkov photon hits that are coincident within roughly 5 ns, while the dark noise hits are random. Once the vertex is reconstructed the time-of-flight subtracted hit times improves the signal to noise ratio. The electron's or positron's direction is reconstructed from the direction of the characteristic 42° opening angle Cherenkov cone. The energy of the event is determined using the observed Cherenkov light intensity.

Above about 10 MeV, this event reconstruction works very well since there are many more Cherenkov light hits (about 60) than hits due to dark noise (about 12 within 220 ns). Near and below 5 MeV sophisticated vertex reconstruction programs are needed, since there are only about 25 to 30 collected photo-electrons from Cherenkov light. Events from radioactive background increase exponentially with decreasing energy. Most of this background comes from the PMTs themselves: the PMT glass and the fiberglass backing the PMT enclosures.

A new electronics and online system replaced the whole data acquisition (DAQ) system [2] in September 2008, starting the SK-IV phase. In the new DAQ scheme, the hardware event trigger for the data reduction is replaced by processing all the hits in the online farm. This enables the lowering of the solar neutrino detection threshold. Using the improved vertex fit program that has been introduced since SK-II [3], a new trigger system, the Wideband Intelligent Trigger (WIT), simultaneously triggers and reconstructs very low energy (above 4 MeV) electrons.

2 New DAQ System

With the former DAQ system, the detector triggered if the analog sum of the received signals exceeded a certain threshold. That reduced the data transfer rate. However, it limited the decrease of the trigger event threshold.

The new front-end electronics is based on a charge-to-time converter and a multi-hit Time-to-Digital converter (TDC) [4]. TCP/IP based readout channels permit obtaining input pulse rates of 85 kHz/ch. In the former system this rate was 1.4 kHz/ch [2]. The new online system is capable of processing large data flow up to 470 MB/s. To handle this flow of data, Gigabit and 10-Gigabit Ethernet technologies

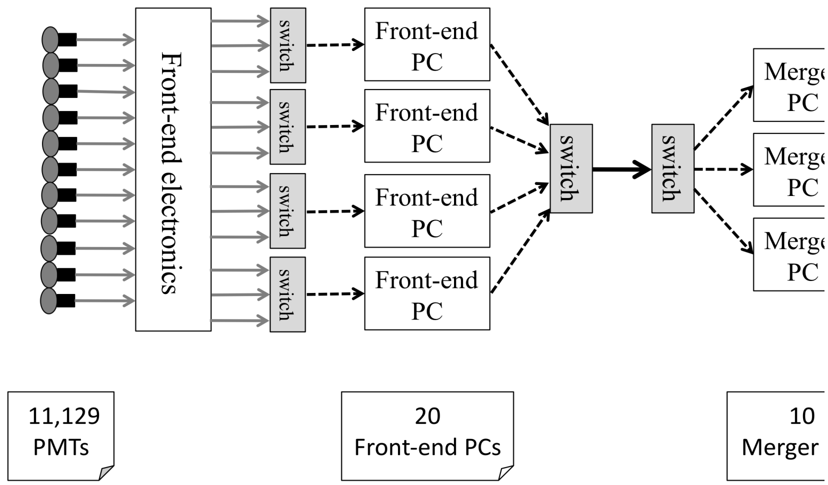

Figure 1: Schematic view of the data acquisition system and the WIT system. The data are transferred to the WIT PCs via Gigabit Ethernet (dashed line) or 10-Gigabit Ethernet lines (bold solid line).

are used and the load is distributed over Linux based PC-s with 2GB RAM and Intel Dual Core CPU (Xeon 5160) operating at 3GHz frequency. In this way, the new DAQ system sends all the data to the online PCs and the event selections is done by software instead of a hardware trigger module.

The online data system consists of 20 front-end PCs which receive all the hit data from the front-end electronics. Data processed in the front-end PCs are then sent to 10 Merger PCs for event building. In the Merger PCs, as suggested by their name, the data are merged and different software triggers are applied to select candidates for various physic-s analyses. From the Merger PCs, the triggered events are sent to an Organizer PC where the data are merged and sort-ed in time order and then written onto the disk for offline analyses. The disk writing speed of the Organizer PC is the bottleneck of the new DAQ system. The maximum value of writing on the disk is about 50 MB/s.

Taking advantage of a cut on the fiducial volume, the Wide-band Intelligent Trigger (WIT) reduces the final data size and the energy threshold can be lowered down to 4 MeV.

3 Event Reconstruction

Electrons below 20 MeV can travel only a few centimeters in water, therefore their Cherenkov light is approximately a point source. The reconstruction of this vertex relies solely on the relative timing of the hits.

WIT uses two different vertex reconstruction algorithms. A fast online fit (Clusfit) pre-filters low energy events, e-liminating isolated hits to reduce the effects of dark noise and reflected or scattered light. More details on the fast fit are given in [5]. If the vertex of the fast online fit is farther than 2 m from any PMT, the event is later reconstructed by a second fit. This procedure reduces both the processing time and the final data size, and it also improves the rejection of the background, in particular the radioactive background originating in the PMT glass and the fiberglass backings of the PMT enclosures.

The second reconstruction algorithm is based on a precise fitter, BONSAI (Branch Optimization Navigating Successive Annealing Iterations), which uses all hits from an event to form the timing residuals to determine the vertex positions.

BONSAI performs a maximum likelihood fit to the timing residuals of the Cherenkov signal as well as the background for each vertex hypothesis. The hypothesis with the largest likelihood is chosen as the reconstructed vertex. This procedure has some technical difficulties due to the accidental coincidence of background hits after the time-of-flight subtraction that can produce local likelihood maxima at several position far away from the global maximum, i.e. the true vertex. Due to the large size of SK, the search for the true global maximum can be tricky and time consuming. To improve speed performances as well as to reduce the number of mis-reconstructions, a pre-reconstruction algorithm (STORE) searches for a good starting position based on a list of vertex candidates calculated from PMT hit combinations of four hits. The time residuals of all four hits in each combination must be zero at its associated point. Any event with four hits or more is reconstructed.

4 The WIT System

The WIT system comprises 2 16-core modules and will work in parallel to the Organizer PC. It will receive the merged data from the Merger PCs before any software trigger is applied, since WIT performs its own trigger.

Each module comprises a HP ProCurve Switch 2900-24G which receives the data flow through 1-Gigabit Ethernet

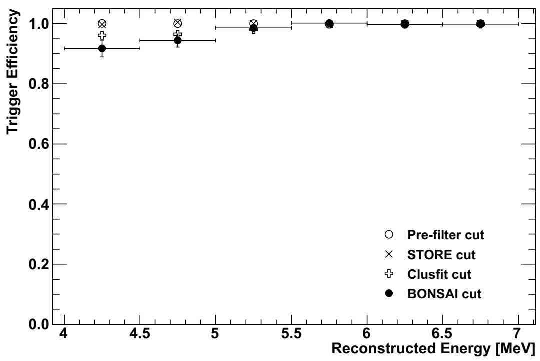

Figure 2: Efficiencies of the trigger criteria as a function of the reconstructed energy. For easier reading, the error bars are drawn only for the last cut.

lines. The switch sends then the data to 2 PCs through 10-Gigabit Ethernet lines. Each Linux based PC comprises 2 Intel Quad Core CPU (Xeon Harpertown 5462) operating at 2.8 GHz frequency and with 16 GB RAM. The block diagram of the WIT system is shown in Fig. 1.

5 Trigger Efficiency

The efficiency of the trigger is evaluated using data from the Ni–Cf light source. A detailed description of this light source is given in [6]. In this study, the Ni source was positioned at (35.3, -70.7, 0) cm with respect to the center of the detector. To subtract the background, data without the Ni source were used.

The efficiency ε is defined as the fraction of events in the source data (N^s) minus the events in the no-source data (N^b) which passes a selection criterion:

$$\varepsilon = \frac{N^s_{cut} - fN^b_{cut}}{N^s - fN^b}$$

The factor $f = t^s/t^b$ takes into account the renormalization according to the different livetimes of the source and the background samples.

Fig. 2 shows the efficiencies of each subsequent trigger criterion as a function of the reconstructed event energy. For easier reading, the error bars are drawn only for the last cut. The pre-filter cut selects the events with at least 11 hits above the dark noise level in the 220 ns window. If the goodness of the pre-reconstruction algorithm STORE is larger than 6.6, i.e. 60% of the 11 hits above the dark noise, then the events survive the STORE cut. When the vertex of the fast online fit (Clusfit) is farther than 2 m from any PMT, the events pass the Clusfit cut. If the reconstructed vertex of BONSAI is also farther than 2 m from any PMT, the events pass the BONSAI cut. Between 4 and 4.5 MeV, the WIT efficiency after the BONSAI cut is 92% ± 3%.

6 Time Performance

The current WIT system has been tested for time performance. Using 1 of the 4 WIT PCs, Fig. 3 shows that the average computing time to process one second of data decreases with the total number of processes run parallel on the same PC. Since each PC has 8 cores, if 9 processes run at the same time, no computing time improvement is observed.

The average computing time can be reduced by roughly 7.8 per PC, i.e. a factor of 31 for the complete system, running parallel the all cores. New commercially available PCs are 4 times faster than the current WIT PCs. Thus, 1 new 16-core PC in addition to the current WIT system will trigger and reconstruct the total Super-Kamiokande data flow at energies as low as 4 MeV.

7 Capabilities of WIT

The motivation for a lower energy threshold is the study of solar (via elastic electron-neutrino scattering) and anti-electron neutrino (via inverse-β reactions) oscillations.

The direction of recoiling electrons from ^{8}B solar neutrino interactions provides a good signature, so a signal to background ratio (after cuts) as low as 5% is possible. Since solar neutrinos are single events, the analysis threshold is defined by the background rate after all cuts are applied. An observation of a solar neutrino signal at 4 MeV would open up the transition region between vacuum and matter oscillation.

A measurement of anti-electron neutrinos requires tagging the produced neutron in (delayed) coincidence with the prompt positron. Such tagging might be done with captures on dissolved Gd ions [7]. SK is able to reconstruct such positrons, with an event reconstruction limit at 3 MeV [8]. Low energy electrons have the same vertex resolution, since the annihilation photons do not produce Cherenkov

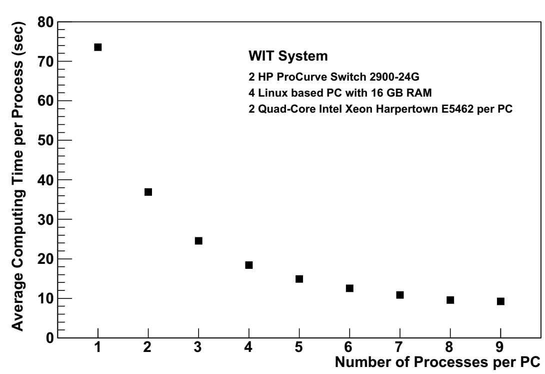

Figure 3: Average computing time to process one second of data as a function of the number of processes per PC. The errors are smaller than the size of the marker.

light. Since the energy threshold of neutrinos (if a neutron capture tag is available) are only limited by the event reconstruction, a 3 MeV threshold should be possible.

In this scenario with neutron tagging, SK should be able to observe few diffuse supernova neutrino background events per year. In addition, the anti-neutrino spectrum from Japan's nuclear power reactors will be collected at a rate of several thousands events per year, allowing the most stringent limits to be placed on solar neutrino oscillation parameters [9].

8 Conclusion

With the introduction of the new DAQ electronics, SK can read out every single hit using a software trigger rather than a hardware trigger. The new trigger system, the Wideband Intelligent Trigger (WIT), simultaneously triggers and reconstructs very low energy electrons. It is specifically designed to trigger with close to 100% efficiency on electrons above 4 MeV and it reconstructs event vertices further than 2 m from any PMT, in order to reduce the computing time and the final data size as well as the radioactive background originating in the PMT glass and the fiberglass backings of the PMT enclosures.

These new tools should enable SK to measure the spectral distortions of the recoil electron energy spectrum from ^{8}B solar neutrino-electron scattering from the transition between matter and vacuum solar neutrino oscillations. Furthermore, if a neutron capture tag is available, SK can do a precise determination of the solar neutrino oscillation parameters with a high statistics neutrino spectrum as well as an observation of the diffuse supernova neutrino background.

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