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Low Energy Event Reconstruction and Selection in Super–Kamiokande–III

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Abstract: Super–Kamiokande–I studied low energy neutrino interactions above 4.5 MeV. Photo-cathode coverage has been restored to 40% in Super-Kamiokande-III in order to observe Cherenkov events with an energy even below 4.5 MeV. This is motivated by the transition of solar neutrino oscillations between vacuum and matter-dominated oscillations near 3 MeV and delayed neutron detection from inverse-beta interactions. I will discuss the progress in event reconstruction and background suppression as well as future measurements which a lower analysis and hardware energy threshold will make possible.

Introduction

Super–Kamiokande is a cylindrical 50,000 ton water Cherenkov detector described in detail in [1]. It is optically divided into an inner 32,000 tons (inner detector, or ID) viewed by about 11,000 inward-facing 20" diameter photomultiplier tubes (PMTs) and an outer 18,000 tons (OD) viewed by outward-facing 8" diameter PMTs. The fraction of surface area covered by the PMT photo cathode is 40%. We see about six photo-electrons from Cherenkov light per MeV. Below about 100 MeV most PMT signals are due to single photon hits. The resolution of the hit arrival time is about 3ns for single photon hits. The dark noise rate is about 5kHz per PMT. Due to the large size of Super–Kamiokande, it takes Cherenkov photons up to 220ns to traverse the detector, and the relative PMT hit times can be used to reconstruct the point of origin (event vertex) of the light. Once the vertex is reconstructed the time-of-flight subtracted hit times separate the dark noise (random) from the Cherenkov photon hits (coincident within $\approx$5ns). The electron's or positron's direction is reconstructed from the direction of the characteristic 42^0 opening angle Cherenkov cone, the energy 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 220ns). Near and below 5 MeV sophisticated vertex reconstruction programs are needed, since there are only about 25 to 30 photo-electrons from Cherenkov light. Also, below 5 MeV 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 of the PMT enclosures (which protect against PMT implosion chain reactions). Due to vertex resolution and mis-reconstruction, these backgrounds reach far inside the detector, and their intensity depends strongly on the quality of the vertex reconstruction program.

Vertex Reconstruction Improvements

To be able to reconstruct low energy electrons in Super–Kamiokande–II which had only about 46% of the 20" diameter PMTs compared to Super–Kamiokande-I and Super–Kamiokande–III, we improved the vertex fit program. In Super–Kamiokande–I we maximized an ad-hoc "goodness" of the Cherenkov signal. Our new reconstruction, BONSAI (branch optimization navigating successive annealing iterations), performs instead a maximum likelihood fit to the timing residuals of the Cherenkov signal as well as the dark noise background for each vertex hypothesis. The hypothesis with the largest likelihood is chosen as the reconstructed vertex. Technically, this is rather difficult, since the accidental coincidence of dark noise hits after time-of-flight subtraction can produce local maxima of the likelihood at several positions far away from the true vertex (or global maximum). The large size of Super–Kamiokande renders the search for the true global maximum tricky and time consuming. Also, most standard maximization strategies are often "caught" by local maxima, if they are close to the starting position. To improve both the speed performance as well as reduce the number of mis-reconstructions, the systematic search for a good starting position with a regular grid (spaced about 4m) was replaced by a search of a list of points. Combinations of four hits define these points by requiring that all four hit time residuals of a combination are zero at its associated point. With BONSAI Super–Kamiokande–II was able to analyze 7MeV electrons recoiling from elastic solar neutrino-electron scattering.

For Super–Kamiokande–III, we improved BONSAI's maximization strategy. BONSAI is now fast enough to be run on-line and has a slightly improved mis-reconstruction ratio. The on-line reconstruction is needed, since the BONSAI vertex provides an "intelligent trigger"[1] for Super–Kamiokande's lowest energy events: all events closer than 2m to any PMT are deleted from the raw data file thereby reducing the number of raw events by more than an order of magnitude.

Event Selection and Background

Low energy events compete with three different types of background: decays from nuclear spallation products induced by cosmic ray muons, external radioactive background and internal radioactive background. External radioactive background originates mostly in the PMT glass and the fiberglass backings of the PMT enclosures. Internal radioactive background is either injected by the water system during recirculation, or instable elements are produced by the detector material and then dissolved in the water (a typical example is radon gas from the U/Th decay chain). Most of the spallation background is reduced by reconstructing muon tracks preceding the low energy event and removing events with good spatial and temporal correlation. The spallation cut produces about 20% of dead time in the detector. Remaining spallation background could come from muon showers (which are hard to reconstruct completely), mis-fit muons, and very long-lived spallation products. Most of the external radioactive background is removed by a vertex cut requiring events to be more than two meters away from any PMT. Since this background is huge, a high rate of external background events survives this cut due to mis-reconstruction of the vertex. Typically, such events have a poor hit time residual coincidence compared to Cherenkov events. For Super–Kamiokande-II we developed a powerful vertex goodness criterion testing the time residual coincidence:

$$g(\vec{v}) = \sum_{i=1}^{N} w_i e^{-0.5(t_i - |\vec{x_i} - \vec{v}|/c)/\sigma)^2},$$

where t_i are the measured PMT hit times, $\vec{x_i}$ the PMT locations, $\vec{v}$ is the reconstructed event vertex, σ is the effective timing resolution expected for Cherenkov events (5ns) and w_i are Gaussian hit weights also based on the hit time residuals, but with a much wider effective time resolution (60ns). The weights reduce the dark noise contamination of the Cherenkov light. We combined this timing goodness with a circular KS test checking the azimuthal symmetry around the Cherenkov cone, which is also sensitive to mis-reconstruction of the vertex. As a consequence, the external radioactive background reconstructing deep inside the detector was reduced by more than an order of magnitude. We are left with the internal radioactive background (radon gas). Since radon produces Cherenkov light from real β decays of its daughter ^{214}Bi it is hard to distinguish such events from true electrons near five MeV. The only difference is the multiple scattering of the electron since the ^{214}Bi decay electrons are lower in energy. Most of this

1. as in Super–Kamiokande–I and II, the intelligent trigger is actually a sucession of two vertex reconstruction programs: a fast, first reconstruction (which was completely redesigned for Super–Kamiokande–III) fits all events while the precise, second fitter (BONSAI) processes only events further than 2m from any PMT according to the first fitter. This procedure reduces the speed performance by a factor of about three. It also improves the background reduction.

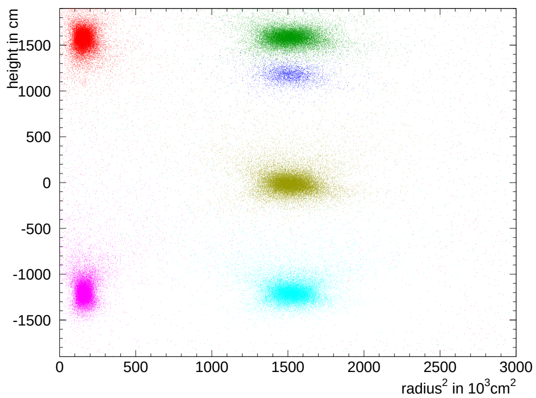

Figure 1: Reconstructed Positions of Single 4.4 MeV Electrons Injected at Six Positions by a Linear Accelerator.

background has to be reduced by changes to the detector hardware (e.g. change of the water flow).

Background Studies for Super–Kamiokande–III

To understand the backgrounds in Super–Kamiokande-III we developed several new sources. We used a linear accelerator to inject single low energy electrons at six different positions in the detector. While this linear accelerator was also used in Super–Kamiokande–I and –II as well, this time we successfully reduced the lowest electron energy to 4.4 MeV. In addition we took data for 4.8MeV and 8.6MeV electrons. The injection positions were $(-3.9, -0.7, +16.0)$m, $(-3.9, -0.7, -12.1)$m, $(-12.4, -0.7, +16.0)$m, $(-12.4, -0.7, +12.0)$m, $(-12.4, -0.7, -0.1)$m, and $(-12.4, -0.7, -12.1)$m. Figure 1 shows the reconstructed vertex positions of the 4.4 MeV data. Although there are a few mis-reconstructions, almost all the events cluster within a few meters of the injection position. All events travel in the downward direction. We are currently using this data to design the cuts of the event selection.

We also made a 60kBq Thorium source combining many camping lantern mantles to understand 2.6MeV gamma ray contamination from ^{208}Tl

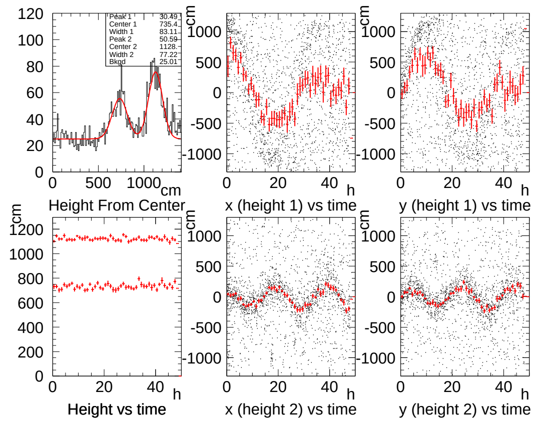

Figure 2: Reconstructed Low Energy Events After Radon Injection. Radon was injected at $(0.4, -0.7, 9.5)$m and $(11.0, -0.7, 5.5)$m. The left, top panel show the reconstructed height, the left, bottom panel the mean height near each injection point as a function of time. The z vertex resolution is 70-80cm. After injection, the radon appears to follow a circular path in the xy-plane around the detector center as shown in the right four panels. The red data points are the mean values of x and y as a function of time.

originating in the fiberglass backing of the PMT enclosures. We are currently studying the transport and decays of radon gas by artificially injecting radon rich water at two points into the detector. Figure 2 shows the path of the resulting "radon bubbles". As expected, the timing goodness and azimuthal symmetry around the Cherenkov cone of the decays is the same as for low energy electrons.

Trigger Energy Threshold of Super–Kamiokande–III

Next year, we plan to upgrade and modernize the Super–Kamiokande electronics. We expect to be able to record every PMT hit using a clock to read out time "chunks" of data. A new intelligent trigger system will then search this data stream for good low energy Cherenkov events and simultaneously reconstruct them. If it reconstructs the vertex further than two meters from any PMT, the

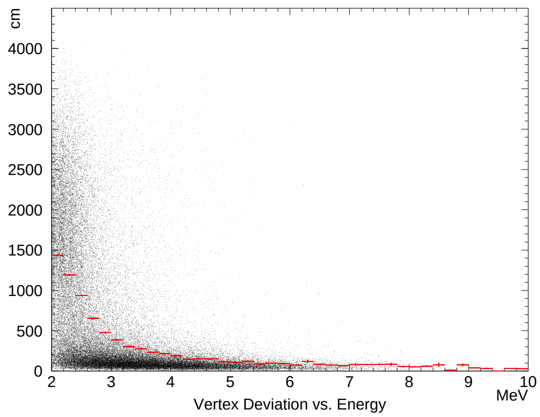

Figure 3: Deviation of the Reconstructed Vertex from the True Position of Monte-Carlo Reactor Neutrino Inverse-β Reactions. The red error bars are the mean deviations as a function of reconstructed energy. Low energy electrons show a similar behavior as the positrons from inverse-β reactions.

event will be written to disk, otherwise it will be discarded. We therefore expect the trigger energy threshold to be only limited by the abilities of the vertex reconstruction.

Capabilities of Super–Kamiokande–III

The motivation for a lower energy threshold in Super–Kamiokande–III is the study of solar (via elastic electron-neutrino scattering) and reactor neutrino (via inverse-β reactions) oscillations. The direction of recoiling electrons from solar neutrino interactions provide a good signature, so a signal to background ratio (after cuts) as low as 5% is possible. A measurement of reactor neutrinos requires tagging the produced neutron in (delayed) coincidence with the prompt positron. Such tagging might be done with captures on dissolved Gd ions [2]. Figure 3 shows the vertex resolution of simulated reactor neutrino events as a function of the reconstructed total positron energy. Super–Kamiokande is able to reconstruct such positrons, if the energy reconstructs above three MeV. Low energy electrons have the same vertex resolution, since the annihilation photons do not produce Cherenkov light.

Since solar neutrinos are single events, the analysis threshold is defined by the background rate after all cuts are applied. Our goal is to analyze solar neutrino events above 4 MeV of total reconstructed recoil electron energy to explore the transition between MSW [3] and vacuum solar neutrino oscillations. Achieving this goal will require further reduction of backgrounds, in particular internal radioactive backgrounds.

The energy threshold of reactor neutrinos (if a neutron capture tag is available) are only limited by the event reconstruction, so a 3 MeV threshold should be possible. Due to its large size, Super–Kamiokande would be able to collect several thousands of reactor neutrino interactions per year and determine the solar neutrino oscillation parameters by itself with unprecedented precision [4] within a few years.

Summary

Many improvements and studies were performed to reduce the Super–Kamiokande energy threshold. These new tools should enable us to do exciting new measurements: distortions of the recoil electron spectrum from solar neutrino–electron elastic scattering from the transition between MSW [3] and vacuum solar neutrino oscillations and a precision determination of the solar neutrino oscillation parameters with a high statistics reactor neutrino spectrum.

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