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Neutron tagging and its physics application in Super-Kamiokande-IV

HAIBING ZHANG[1] FOR THE SUPER-KAMIOKANDE COLLABORATION
Department of engineering physics, Tsinghua University, Beijing, China
zhanghb02@mails.tsinghua.edu.cn

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Abstract: With the electronics upgrade in 2008, the fourth phase of Super-Kamiokande (SK) is now capable of detecting thermal neutrons from neutrino interactions with $\sim 20\%$ efficiency. Observation of neutrons produced in atmospheric neutrino interactions is presented. Preliminary results of a background study for the supernova relic neutrino (SRN) detection are shown. Prospects of future SRN searches and possible improvement of background rejection for proton decay searches with neutron tagging in SK-IV and beyond are also discussed.

Keywords: Neutron tagging, water Cherenkov detector, supernova relic neutrino, proton decay

1 Introduction

Tagging neutrons produced in neutrino interactions with water can extend the physics scope of water Cherenkov detectors (WCD). For example, a delayed-coincidence detection of positron and neutron capture offers a powerful way to identify low energy anti-neutrino via the inverse beta decay reaction (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$. This is of crucial importance to allow the detection of SRN. Neutron tagging could also improve proton decay search sensitivity by rejecting potential atmospheric neutrino backgrounds accompanied by neutrons.

Two independent methods were proposed to add neutron tagging capability for WCD's. The first approach [1] involves doping water with water soluble compound of gadolinium, neutron capture on which yields gamma cascades with total energy ~8 MeV. These relatively high energy γ-rays should be readily seen by a WCD such as SK whose trigger threshold is typically ~5 MeV. In the second approach [2], a new trigger logic is introduced to force the DAQ system to take 500 μs data without threshold after each primary event (e.g. e^+ in IBD) above the so-called super-high-energy (SHE) trigger (~10 MeV). A search of 2.2 MeV γ emitted from neutron capture on free proton is then performed off-line exploiting the spatial and temporal correlation between neutron capture and the primary event. After the successful demonstration of detecting neutron capture in SK-III [3], the forced trigger scheme has been incorporated into the new SK DAQ system which was upgraded in 2008.

2 Neutron tagging in pure water

The 2.2 MeV γ generates only ~7 PMT hits on average in SK and in general can not be precisely reconstructed on its own due to PMT noise interference. But the neutron produced in inverse beta decay is typically of low energy, which is quickly thermalized and captured with a free mean path ~50 cm. So to a good approximation, the 2.2 MeV γ shares a common vertex with the primary event, which is used to do a time-of-flight (TOF) correction. A 10 ns sliding window is then applied to search candidate timing peaks above PMT noise. Backgrounds include PMT noise, radioactivity from surrounding rock and radon contamination in water, etc. In this study, the 2.2 MeV γ detection efficiency is evaluated using Monte Carlo (MC), while the background probability is estimated using SK-IV real data.

2.1 Selection criteria for neutron capture events

To identify the 2.2 MeV γ from candidate timing peaks, the following criteria are used first:(1) Number of hits in the 10 ns window (N10) is greater than 7; (2) No major cluster hits (Ncluster), $\mathrm{N10} - \mathrm{Ncluster} > 5$; (3) Less backward going hits (Nback), $\mathrm{N10} - \mathrm{Nback} > 6$; (4) Less hits that have low hit probability (Nlow), $\mathrm{N10} - \mathrm{Nlow} > 4$. After this stage of pre-selection, the signal efficiency and background probability are 20.8% and 3.9%, respectively.

A further reduction utilizes the likelihood ratio constructed from four discriminating variables: number of PMT hits around N10 peak in 300 ns widow (N300 - N10), root mean square (RMS) of PMT hit timings (T_{rms}), RMS of azimuth angle of hit vectors along the estimated direction (ϕ_{rms}), and mean angle between hit vectors and estimated direction (θ_{mean}), as shown in Fig. 1. Requiring the likelihood

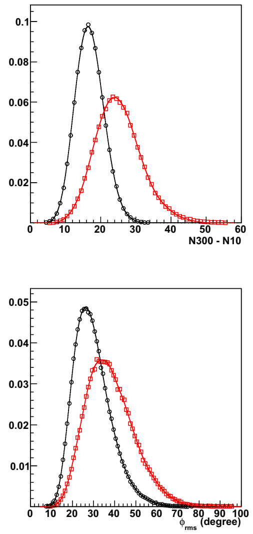

Figure 1: Normalized distributions of N300 − N10 (a), Trms (b), ϕrms (c) and θmean (d). The points represent signal (circle) and background (square) histograms and the lines indicate corresponding PDF's.

ratio to be greater than 0.35, the background probability is brought down to 1%, while the signal efficiency is 19.3%.

2.2 Verifying neutron tagging efficiency using an Am/Be source

To verify neutron tagging efficiency given above, experimental tests were conducted with an Am/Be source embedded in a bismuth germanite (BGO) scintillator. The prompt and delayed event-pair is generated via: $\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^{*} + n$; ${}^{12}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma$(prompt); $n + p \rightarrow d + \gamma$(delayed). The scintillation light induced by 4.43 MeV deexcitation γ serves as the primary event. Note that the reaction to the ground state of ^{12}C also exists, where no 4.43 MeV deexcitation γ is emitted. The experimental apparatus was deployed at the center of the tank, during which the trigger gate to catch 2.2 MeV γ was temporarily enlarged to 800 μs in order to obtain a complete neutron capture time spectrum. To estimate source related background (e.g. ground transition neutron), 10 Hz 800μs random trigger data was also taken.

The final N10 distribution after all cuts applied is shown in Fig. 2, where for Am/Be data all backgrounds are subtracted according to random trigger data. Signal efficiencies for MC and data are (19.2±0.1)% and (19.0±0.2)%, respectively. Data is in good agreement with MC. Fig. 3 shows the distribution of time difference (ΔT) between delayed neutron signal and prompt event. The neutron lifetime in pure water is measured to be $(201.8 \pm 4.7)\mu$s using a unbinned maximum likelihood fitting as shown in Fig. 3.

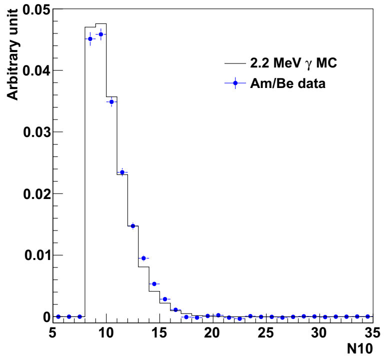

Figure 2: Comparision of N10 between Am/Be data and MC after all cuts applied.

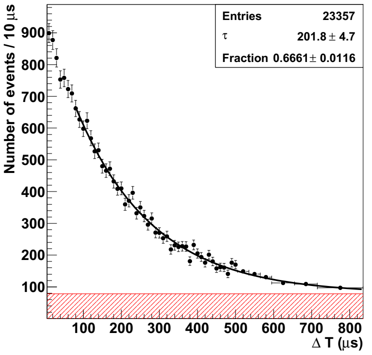

Figure 3: Distribution of ΔT. Shaded histogram indicates background.

3 Observation of neutrons in atmospheric neutrino data

In atmospheric neutrino events, neutrons can be produced in neutrino interactions (e.g. inverse beta decay) as well as secondary interactions from daughter products. A search of neutrons in fully-contained (FC) neutrino events is conducted using 740.2 live days of SK-IV atmospheric neutrino data. The final N10 after likelihood cut is shown in Fig. 4, where the fraction of accidental background is estimated from the known background probability (1%) and the rest are assumed to be neutron capture signal. The expected spectrum is reproduced by data fairly well. Fig. 5 shows the ΔT distribution together with the fitted neutron lifetime, which is consistent with the measurement using an Am/Be source. Both figures demonstrate, for the first time, a clear observation of neutrons produced in neutrino interactions in a water Cherenkov detector.

Fig. 6 shows neutron yield (number of neutrons in one event) as a function of visible energy of atmospheric neutrino events. It can be seen that above 100 MeV (visible energy), on average more than one neutron is produced per

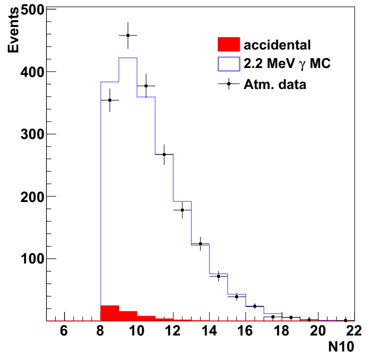

Figure 4: Final N10 of neutron candidates in atmospheric FC data.

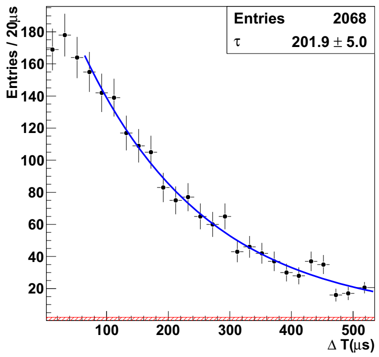

Figure 5: Distribution of ΔT of neutron candidates in atmospheric FC events. Shaded histogram show expected accidental background.

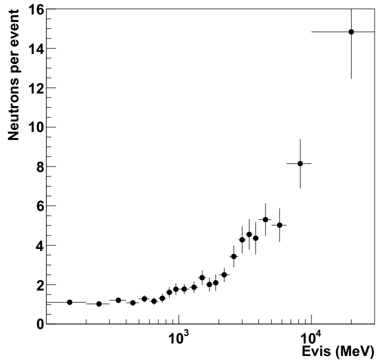

Figure 6: Efficiency corrected neutron yield as function of visible energy.

event. And in general the higher visible energy, the more neutrons are produced. The neutron multiplicity is shown in Fig. 7.

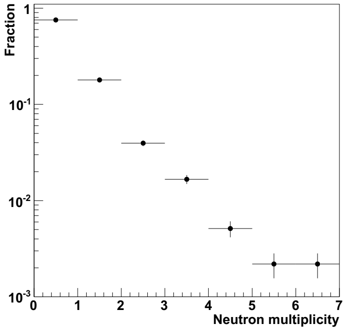

Figure 7: Neutron multiplicity per event.

4 Background study for SRN detection

SRN is most likely to be detected in SK via the inverse beta decay reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. Current SK sensitivity is limited by cosmic-ray muon induced spallation products (below 16 MeV) and decay electrons from sub-Cherenkov muons produced by atmospheric neutrinos (above 16 MeV). Tagging the neutron in inverse beta decay will improve SK's sensitivity by rejecting most decay electrons, as well as opening up lower energy window. Study of SK-IV data can provide valuable insights into neutron correlated backgrounds to the SRN search, estimation of which is still largely uncertain.

Currently four major backgrounds remain for the SRN search: $\nu_\mu/\bar{\nu}_\mu$ CC decay electrons, $\nu_e/\bar{\nu}_e$ CC, NC elastic and heavy particle (μ/π) leakage. Events without a delayed neutron capture signal can be rejected. SK-IV data reveals that neutrons can also be produced in neutrino interactions (other than anti-neutrino interactions) at relevant energies, e.g. the out going proton in $\nu_\mu + n \rightarrow \mu^- + p$ can induce neutrons while propagating in water.

Fig. 8 shows the energy spectrum (line) and observed number of neutrons in each energy bin (points) in SRN search side bands:(1) events with two Cherenkov rings, (2) events with decay electron(s) or having a preceding nuclear gamma, (3) mu-like events, (4) isotropic events from NC processes and (5) pion events. Neutrons are seen in all the side bands. Taking into account the efficiency, the observed average yield is close to 1 neutron per event. It is clear that not all neutrons are induced by anti-neutrino interactions. Neutrons from neutrino interactions must also have a significant contribution. Below 30 MeV where SRN events are most likely to occur, NC background stands out to be the most important one, not only because has it the similar rising spectrum but also it's often accompanied by neutrons. However, multiple neutrons are possible, as shown in Fig. 9. Especially for NC events, a MC study shows that more than one neutron is produced most of the time, which is supported by SK-IV data, as shown in Fig. 8 (4) and Fig. 9 (4). These NC events can be rejected if multiple neutrons are detected. Hence higher neutron tagging

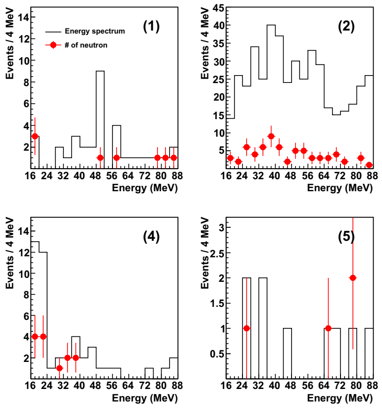

Figure 8: Energy spectrum and observed number of neutrons in SRN search side bands. Solid line represents the reconstructed energy assuming an electron and points indicate the number of neutrons observed in each enrgy bin.

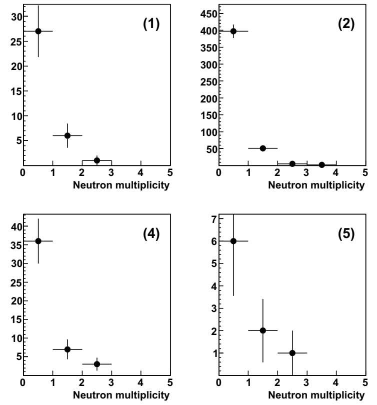

Figure 9: Observed neutron multiplicity in SRN side band events.

efficiency is desirable, which can be achived by the other neutron tagging method, i.e. loading SK with gadolinium (GADZOOKS![5]).

5 Prospects and outlook

Neutron tagging can also play an important role in proton decay searches. Taking $p \rightarrow e^+\pi^0$ as an example, the estimated background rate is 2.1 ± 0.3 ± 0.8 events/megaton·year[4], which arise mainly from atmospheric neutrino interactions. Some background process are: (a) $\nu_e + p \rightarrow e^- + p + \pi^+$; (b) $\nu_e + n \rightarrow e^- + p + \pi^0$; (c) $\nu_e + n \rightarrow e^- + n + \pi^+$; (d) $\nu_e + n \rightarrow e^- + p + \pi^0$. The outgoing proton in (d) induces neutrons through hadronic interaction in ^{16}O. Process (a) and (b) do not have neutrons in the final state and remains irreducible. Process (c) and (d) can be rejected if neutron in the final state can be identified. Table 1 shows neutron yield in $p \rightarrow e^+\pi^0$ search side band (total momentum < 500 MeV/c, 700 MeV/c^2 $<$ total invariant mass < 1200 MeV/c^2), from which one can estimate how many backgrounds can be reduced by tagging neutrons. For example, ∼23% backgrounds can be rejected by tagging neutrons in pure water. In case of a Gd-loaded detector, ∼56% backgrounds can be rejected assuming neutron tagging efficiency is 67.7% [3]. Note that this is a conservative estimation since the simulation of neutron production is incomplete in current MC.

# of neutrons in one event	Fraction (%)
0	31.5
1	30.1
2	18.2
3	9.2
4	5.2
>=5	5.8

Table 1: Neutron production in proton decay background.

In sum, a new trigger logic has been implemented in SK-IV to tag thermal neutron captures in pure water. Neutron tagging efficiency and background probability are found to be, respectively, 19.3% and 1%. Signal efficiency and neutron capture time in pure water is well verified using an Am/Be source. Clear neutron capture signal is observed in atmospheric neutrino data, which demonstrates the potential to reject backgrounds for future proton decay searches. Precise estimation of NC contribution and neutron production in NC events are of high priority for future SRN search programs.

Intense R&D is currently underway towarding a gadolinium-enhanced SK. Higher efficiency and lowered energy threshold are expected to greatly improve SK's sensitivity to the SRN search in future.

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