PROCEEDINGS OF SCIENCE

Reconstruction of Spallation Neutron Kinematics in Antineutrino Detectors of the Daya Bay Experiment

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In this contribution, we present our study of the neutron initial vertex and energy at the beginning of its scattering process inside an organic scintillator detector. A method is developed to reconstruct the proton recoil events excited by fast neutrons. From physics data, we derive the preliminary selection of muon samples that correlate with spallation neutron captures. Monte Carlo simulation of muons and neutrons in our antineutrino detector is carried out to study all possible interactions and selection efficiency for fast neutrons.

XVI International Workshop on Neutrino Telescopes,
2-6 March 2015
Palazzo Franchetti âĂŞ Istituto Veneto, Venice, Italy

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PoS(NEUTEL2015)074

1. Introduction

Fast spallation neutrons from cosmic-ray muons are essential candidates of background signals in underground neutrino experiments. We study their properties in the Daya Bay antineutrino detectors (ADs) with a method that is also applicable to other scintillator based neutrino detectors. The energetic cosmic-ray muons can penetrate kilometers of rocks and reach at our ADs, causing scintillation through various physical processes; it may also cause the spallation of a nucleus, producing isotopes and fast neutrons[1, 2, 3] . Fast neutrons scatter with protons, and the latter recoil and cause scintillation in liquid scintillator, all happen in a transient from the passage of muon. Both types of muon events involve muons entering ADs and passing near ADs are vetoed in Daya Bay Experiment[1], the latter of which produces fast neutrons that can spill into ADs and be captured; both types of muon events mimic the prompt-delay pairs of the desired inverse beta decay (IBD).
Hence it is important and worthwhile to establish a new method to study the spallation neutron and proton recoil with AD muons, whose contributions of scintillation sum up in the PMT pulses and cannot be separated easily.

2. Reconstruction Method

In this contribution, we introduce our reconstruction procedures that are used to extrapolate the initial kinematics of the neutron once it is created through spallation processes in the ADs. As the energetic cosmic-ray muons penetrate the ADs, they create scintillation signals that are picked up by Daya Bay trigger system. *Prompt 1*: Muon entering AD, depositing energy through ionization, Bremsstrahlung and Cherenkov effects; *Prompt 2*: Fast neutron(s) produced by nuclei spallation[4], protons received energy from spallation neutron and recoil; *Delayed*: Neutron captured inside AD on Gadolinium or Hydrogen.

The two prompt signals are easily overlapped in a single muon readout, hence we impose the following steps to separate their contributions with a simplified model(*Figure 1*):

I. Select isolated AD muon events with deposited energy above 60 MeV and high direction precision, derive their position and momentum information.

II. Calculate the scintillation contribution of muon for each PMT, by arranging scintillation points along its trajectory according to the muon average stopping power(*Figure 2*); subtract this value from the charge collected by each PMT.

III. Using the subtracted values in each PMT signals to reconstruct the energies and verticies of proton recoils by treating them as a point source of scintillation.

IV. Implement proper time cut(10-200μs) & energy cut(1.7-12MeV)[1] and reconstruct the neutron capture; for better reconstruction performance of proton recoils, select those prompt-delayed pairs that only *one* neutron is found captured within the time window.

The stand-out scintillation from proton recoils indicate the initial state of the spallation neutron from its creation, as the kinetic energy of the neutrons are deposited to the protons through

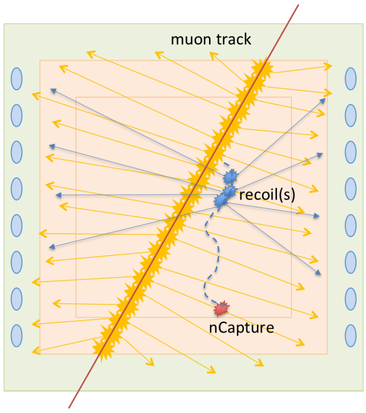

Figure 1: The simplified model to reconstruct proton recoil from AD muon signals. The red solid line denotes an intercepting muon, the blue splash denotes the protons recoil scintillations, and the red splash denotes the delayed neutron capture.

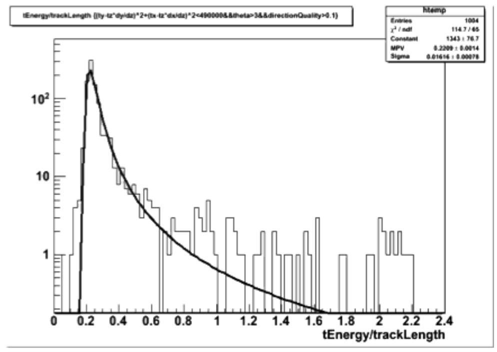

Figure 2: We calculate the energy deposition rate for near vertical muons whose $E_\mu > 60$ MeV with high directional precisions. The muon stopping power and its Landau fitting shows a maximum at (0.2209±0.0014) MeV/mm.

elastic or inelastic scatterings. Therefore, the fast neutron energy and vertices are indicated by the proton recoil. We propose two pre-evaluation indices to discriminate whether a muon is associated with the spallation process:

1. The difference of the remainder PMT response compared to a reconstructed point-sourced pattern, denoted by its $\chi^2 = \sum_{i=1}^{192} \frac{(N^i_{recon} - N^i_{real})^2}{(\delta^i_{real})^2}$. Here N^i_{recon} and N^i_{real} denote the reconstruction expectation and truth value of nominal charge at ith PMT, with the uncertainty $\delta^i_{real} = \sqrt{N^i_{real}}$.

2. The signal to background ratio of the reconstructed proton recoil energy over the total muon deposited energy, defined as the spallation quality $Q_{Spall} = E_{recoil}/E_{total}$.

Also, after each proton recoil vertex reconstruction, we calculate its perpendicular distance to the parent muon track, its distance to subsequent neutron capture site, and the scattering angle between the muon track and the line connecting initial(proton recoil)-final(neutron capture) vertices. The three quantities are denoted as D_{track}, D_{np} and α_{scat} respectively in this article.

3. Data Analysis

The physics data in Daya Bay Experiment are used to test our generic algorithm. Here we show some preliminary results for verification and implication.

3.1 Comparison Between 1 and 0 Neutron Capture

We repeat the proton recoil reconstruction with muons that have no neutron capture observed in the delayed signal window, using the exact same selection as in the previous chapter. For the muons with a delayed neutron capture event, the reconstruction result is dominated by the proton recoil signal, while the reconstruction of zero neutron events is dominated by the background. We plot the reconstruction parameters(χ^2,Q_{Spall}, D_{track}, D_{np} and α_{scat}) in 2D histogram, and subtract the single neutron capture pattern by the zero neutron capture pattern with the same statistics.

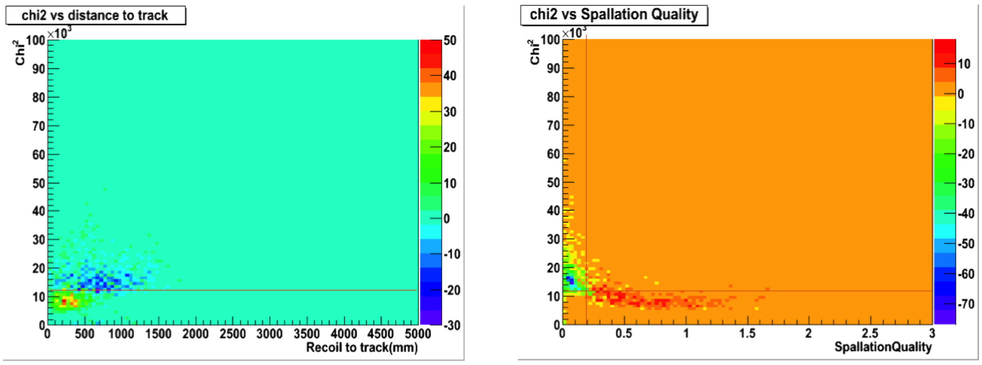

Figure 3: *Left panel*:The subtracted χ^2&D_{track} distribution, where signals are concentrated closer to muon tracks with χ^2<12k. *Right panel*:The subtracted χ^2&Q_{spall} distribution, indicating a viable background veto with Q_{spall}>0.2 and χ^2<12k.

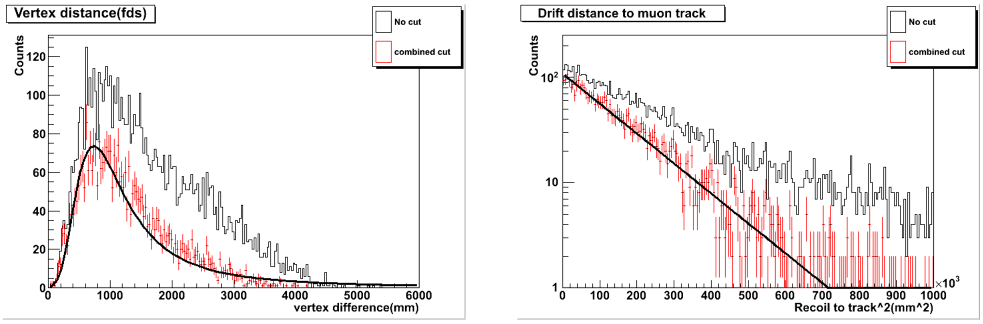

Figure 4: *Left graph*:The distance between the reconstructed proton recoil and neutron capture being fitted to a Landau function. The average mean free path of fast neutron inside the AD is about one meter. *Right graph*:The reconstructed proton recoil vertex from muon track plotted with R^2, which is fitted to an exponential function.

The result (*Figure 3*) shows a correlation of proton recoil with delayed neutron capture events, and the index obtained in the fitting places a handle on selecting spallation proton recoil signals.

3.2 Analysis Results

We use the veto values Q_{spall}>0.2 and χ^2<12k in *Figure 3* to derive the final distribution of D_{track}, D_{np} and α_{scat}, we show the D_{track} and D_{np} distributions as an example in *Figure 4*, with red lines denote our dataset with final selection.

This very preliminary result shows the mean free path of the spallation neutrons, and the decaying trend of its production site from the parent muon track. Further efforts to optimize the selection parameters and to obtain the cut efficiency require the toy Monte Carlo (MC) simulations with truth information of muons, neutrons and protons.

4. Monte Carlo Simulations

A *GEANT4* based toy MC simulation with full detector geometry model is performed to study the difference between our reconstruction result and the truth value. The muon Monte Carlo sample

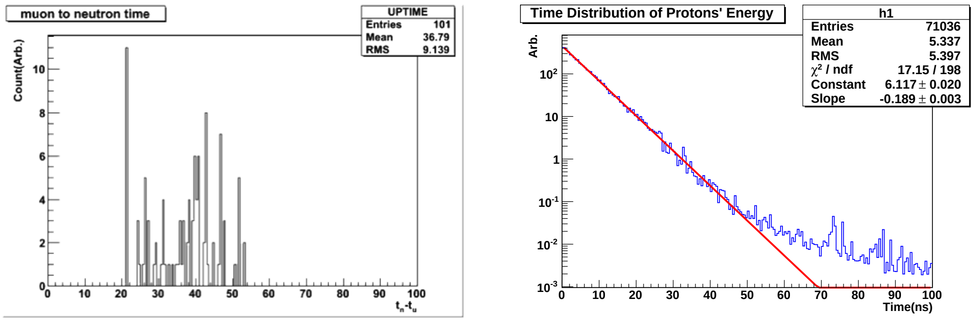

Figure 5: Truth information of time. *Left panel*:Time from muon generation to neutron production(time in nanosecond). *Right panel*:The energy received by protons since the neutron was produced was plotted with time. Each slice of the histogram represents $\sum_{allneutron}(dE_p)/(\int_{t=0}^{\infty} E_p dt)$. The final distribution is fitted with an exponential function $E_p(t) = const. \cdot 10^{-0.189t}$, which shows 99.9% of the proton energy is acquired within 40ns since the neutron is produced.

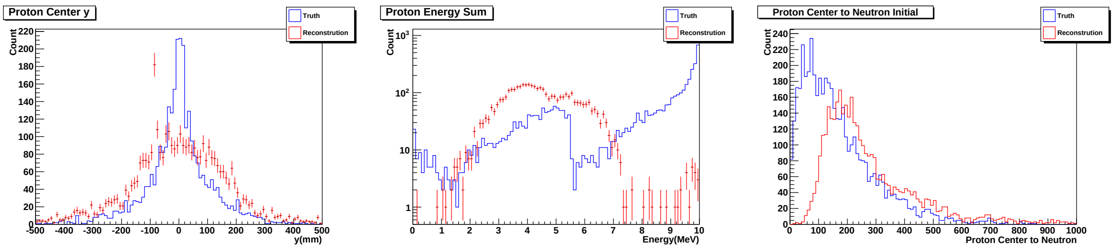

Figure 6: Truth vs. Reconstruction with 10MeV neutron. *Left panel*: Vertex of proton recoil signals in y-axis. For multiple proton recoils in a single event, we use the center of energy $\frac{\Sigma \mathbf{r}_i \cdot E_i}{\Sigma E_i}$ to represent the truth value. *Middel panel*: Sum of proton recoil energies after each neutron.The difference between the truth and reconstructed spectrum is due to the proton quenching of LAB based scintillators[6]. *Right panel*:The distance between neutron production site and effective proton recoil site(center of energy). The spectrum is shifted outwards in the reconstruction result.

is generated using Daya Bay muon flux profile[5]. To study the proton recoil process of fast neutrons with higher statistics, we also simulate isotropic neutrons with energy levels from 1-10MeV at the center of AD.

We verify by simulations that the average time interval from muon passing through ADs to the spallation neutron causing protons to recoil is at a scale less than 100ns, for which the contribution of proton recoil will be admitted in a single AD muon readout(*Figure 5*). Nevertheless, using our reconstruction method, we find a good match in reconstructed and truth values at higher energy level(*Figure 6*), while the performance is worse when the initial neutron energy is less than 3MeV. The larger offset in the last plot is an expected consequence due to the uncertainty in reconstruction algorithm.

5. Conclusion

An algorithm in reconstructing proton recoils from muon trigger events has been proposed and tested with Daya Bay dataset. We demonstrate our method to derive the initial position and energy of the spallation neutrons. We further verify this method by studying the truth information

PoS(NEUTEL2015)074

in Monte Carlo simulation. There is still room of improvement for this study. For example, the vertex reconstruction based on charge center calculation has a non-negligible uncertainty, whose effect needs to be suppressed with larger statistics. Also, we used neutrons of discrete energy values in the AD center to simulate the spallation neutron because of the low statistics of fast neutron in our muon simulation. However, in reality the spectrum of such neutrons are continuous and they are distributed among the whole volume of AD.

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