PROCEEDINGS OF SCIENCE

# Distinguishing $\nu_\tau$ neutrinos using the neutron echo technique with next generation ice Cherenkov telescopes

**Kareem Farrag,**[a,*] **Colton Hill,**[a] **Wataru Iwakiri,**[a] **Aya Ishihara,**[a] **Myoungchul Kim,**[a] **Maximilian Meier,**[a] **Ryo Nagai,**[a] **Koji Noda,**[a] **Yasutsugu Morii,**[a] **Aske Rosted,**[a] **Anna Pollmann,**[a] **Nobuhiro Shimizu**[a] **and Shigeru Yoshida**[a]

[a] *Chiba University,*
*Dept. of Physics and Institute for Global Prominent Research, Chiba University, Chiba 263-8522, Japan*

*E-mail:* kfarrag@chiba-u.jp

In next-generation neutrino water and ice Cherenkov telescopes, game-changing algorithms will be required to advance our understanding of astrophysical neutrinos, as well as neutrino oscillation properties. Most astrophysical neutrinos arrive with energies below the TeV scale, whereby event flavour identification is challenging. Notably, distinguishing cascades from $\nu_\tau$ interactions versus $\nu_e$ becomes tenuous due to the short length scale propagation of the outgoing $\tau$ lepton. Furthermore, muons produce dimmer tracks at these energies as they minimally ionise during their propagation. Hence, dedicated techniques are required in an attempt to extract neutrino flavour information for such sub-TeV events. Interestingly, hadronic cascades produced in $\nu_\tau$ interactions are expected to yield more neutrons than $\nu_e$ or $\nu_\mu$. These neutrons are then eventually captured by ice molecules, emitting a delayed 2.2 MeV $\gamma$ emission at least $O(100\ \mu s)$ after the prompt photon emission. In this investigation, we analyse simulated event distributions from neutron captures on ice molecules. We report key features of neutron capture events, their timing distributions and expected light yields as a function of energy, and discuss their potential impact to distinguish $\nu_\tau$ events from $\nu_e$ events.

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# 1. Introduction

## 1.1 Neutrinos and their flavours

Our understanding of astrophysical neutrinos has improved immensely over the past six decades, with the measurement of TeV to PeV diffuse neutrinos [1], covering distances of $O(100\,\mathrm{Mpc})$ that is opaque to other astrophysical messengers such as photons. Future observations in next generation ice Cherenkov detectors are designed to be sensitive to atmospheric neutrinos, but also the astrophysical neutrino spectrum for energies below the TeV threshold, which alongside their optical counterparts, will permit multi-messenger searches for $\gamma$ ray sources [2]. This would uncover the low energy tail of the astrophysical neutrino flux, whether it follows a more complicated spectrum than a single power-law, as well as to pin down fundamental properties of $\gamma$ ray sources. In order to achieve objectives of understanding the properties of the lower energy astrophysical neutrino flux, one key pursuit is better understanding of the tau neutrino.

Neutrinos come in three different flavors: electron neutrinos ($\nu_e$), muon neutrinos ($\nu_\mu$), and tau neutrinos, each associated with a corresponding charged lepton (electron, muon, and tau). As these neutrinos propagate, they mix between their flavour eigenstates, producing a different composition of each flavour neutrino at the Earth. One task to further our knowledge of tau neutrinos properties are their cross sections. Neutrinos in particle colliders searches between GeV and TeV energies are being studied [3] and are able to measure the interaction cross sections between these energies for all three flavours. These will complement searches for astrophysical neutrinos by reducing the uncertainty on previously unmeasured cross-sections. Generally, the detection and study of electron and muon neutrinos is often described as more successful with regards to atmospheric and astrophysical searches. In comparison, identifying tau neutrinos has proven to be more challenging, particularly in the case of those from astrophysical origin. In ice-Cherenkov telescopes, this is primarily dominated by our difficulty in distinguish the morphology of electromagnetic versus hadronic cascades, a primary signature for both $\nu_e$ and $\nu_\tau$ events [4].

Tau neutrinos are primarily produced in high-energy processes. Rarely do they appear in neutrino production from cosmic rays with the Earth's atmosphere [5]. Rather, they are predicted to appear as a result of propagation from astrophysical sources like supernovae or active galactic nuclei. Compared to electron and muon neutrinos, tau neutrinos are expected to be the least abundant in the case of atmospheric neutrino production (low energies are dominated by pion production processes in the ratio $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$. Furthermore, assuming that Nature favoured normal ordering between the mass eigenstates, tau neutrinos would be mostly made up of the heaviest neutrino mass state. As a result, tau neutrinos are more likely to undergo oscillations, where they can change from one flavor to another as they travel through space.

In addition, the interaction properties differ for different flavour neutrinos, up to their partner lepton masses and thus their allowed kinematical phase space. When electron neutrinos ($\nu_e$) or tau neutrinos ($\nu_\tau$) undergo charged current (CC) interactions, they can produce electrons ($e^-$) or positrons ($e^+$), respectively. These charged leptons can traverse through the ice, losing energy primarily through ionization, bremsstrahlung, and, at higher energies, through pair production. The energy loss processes cause the electrons/positrons to slow down over short distances and deposit their energy along their paths.



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Muon neutrinos ($\nu_\mu$) participating in CC interactions generate muons ($\mu^-$) as the daughter particles. Muons are highly penetrating that can travel significant distances (up to $O(km)$) in the ice. At sub-TeV energies they lose energy through ionisation, resulting in a gradual energy deposition of $\sim$ 2 MeV/cm along their trajectories. These produce dim tracks. At energies above the TeV scale, they deposit stochastic energy depositions with the ice.

In comparison, tau neutrinos ($\nu_\tau$) in CC interactions with an energy above $E_\nu \gtrsim m_\tau = 1.7$ GeV produce tau leptons ($\tau$). Due to their short lifetimes, $\tau$ leptons typically decay before they can travel a considerable distance in ice, which between GeV and TeV energy corresponds to approximately 49 $\mu$m/GeV (so $O$(mm)) distances. The dominated decay modes of $\tau$ leptons can lead to the production of various daughter particles, such as muons, electrons, pions, neutrons, and neutrinos. These secondary particles interact with the ice through processes like ionization, radiation, and energy deposition, cascading down in energy as they continue to interact with the ice.

### 1.2 Motivation for the neutron echo technique

In order to improve the identification and characterization of $\nu_\tau$ events, the neutron echo technique may be a promising candidate for lower energy neutrino events [6]. In the GeV - TeV range, the CC interaction cross-section is larger than the NC interaction. In the case of $\nu_\tau$ interaction greater than a few GeV, this means production of a $\tau$ lepton is favoured compared to the probability of a NC interaction.

The tau lepton then has total branching fractions to decay hadronically (64.79%) and electromagnetically (35.21%) respectively [7]. It is the only lepton capable of decaying into hadrons due to its sufficiently large mass. In its dominant hadronic decay modes, up to four hadrons (mainly pions or kaons) are produced through $\tau$ decays (the largest being $\tau^- \longrightarrow \pi^-\pi^0\nu_\tau$ with branching fraction 25.49%). Following this, the outgoing particles hadronize the surrounding ice material, producing a collection of neutrons. These neutrons may or may not be thermal in energy. As the neutrons propagate through the ice, they subsequently are moderated and scattered due to the presence of hydrogen in the ice molecules, and via oxygen to a lesser extent. This scattering results in frequent interactions, reducing the mean free path of the propagating neutrons. Since the lifetime of neutrons is $\tau_n \sim 887$ s, almost 100% of the neutrons will decrease in energy before they capture on ice molecules, particularly hydrogen, around the thermal neutron energy scale. Neutrons captured by atomic nuclei in the ice then emit 2.23 MeV gamma rays. Given that the gamma ray has a radiation length of $X_0 = 39.75$ cm, it's pair production length is approximately $\frac{9}{7}X_0 \sim 51$ cm.

Following this, an $e^-e^+$ pair can be produced (although, occasionally the $\gamma$ may also Compton scatter in the ice before it pair produces). Because of the surrounding medium, the $e^-e^+$ may be asymmetrically distributed in energy, summing to 2.23 MeV. We can make a simple estimation for the amount of late light produced per neutron capture as follows. In order to radiate Cherenkov photons, the $e^-e^+$ need a minimum kinetic energy of $T_{e^\pm} = 0.26$ MeV. Assuming the average number of photons emitted by Cherenkov radiation yields that the $e^-e^+$ will emit 270 photons every centimeter travelled by the electron or positron. Approximately therefore, the electrons will fall below energy threshold and stop producing Cherenkov emission around $3X_0 + \frac{9}{7}X_0 \sim 170$ cm away from the pair production vertex. Assuming the maximum range for either $e^-$ or $e^+$, we expect approximately 3000 photons to be radiated per capture at times greater than $O(100\ \mu\text{s})$ which can be detected by optical modules, or other radiation sensors. The timing and spatial distribution of these neutron capture events provide valuable information for identifying $\nu_\tau$ interactions.

Therefore, in this ongoing work, we simulate $\nu_\tau$ interactions to study the neutron echo technique in an attempt to characterise whether this technique can effectively identify $\nu_\tau$ interactions and whether it can be applied to future higher resolution ice Cherenkov telescopes.

## 2. Simulation Procedure

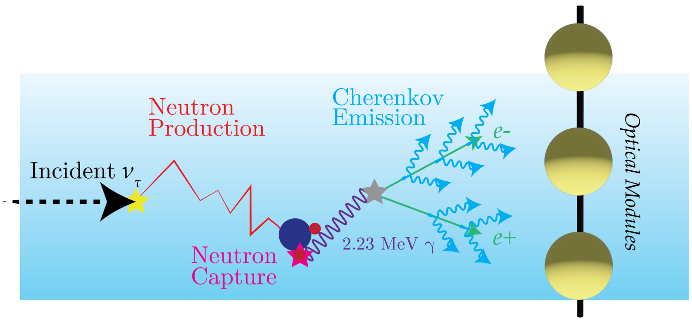


**Figure 1:** Illustration depicting how a neutron echo might be produced in ice. Black shows an incident $\nu_\tau$ interacting at the position depicted by the yellow star. This interaction can produce hadronic daughter particles which go on to produce neutrons through their scattering with the ice as well as their decay products. The neutron typically captures on hydrogen atoms, subsequently emitting a 2.23 MeV $\gamma$ photon. This subsequently proagates through the ice, and can pair produce into a $e^-e^+$ pair whose total energy equals that of the mother photon. These propagate approximately a few radiation lengths in ice, and emit Cherenkov as well as scintillation light during their propagation.

In order to parameterise the rate of neutron captures, as well as the spatial and timing distributions, we needed to generate neutrino interactions in-ice, and propagate their daughter particles. Subsequently as they interact during their propagation through the ice, neutrons are subsequently produces, which moderate in energy throughout the medium until they capture on atoms.

To understand the profiling of the neutrons throughout the interaction, we set up a two step simulation; first to generate neutrino interactions using the GENIEv3 [8] neutrino generator, and then to subsequently propagate their daughters using the GEANT4.11 [9] simulation package, storing information about their resulting neutron capture events.

We sampled $10^4$ neutrinos at fixed energies in multiples per decade, i.e., of the form $i \times 10^j$ GeV, for $i = 1, 2, \ldots 9$ and $j = 0, 1, 2$. For simplicity, at each given incident neutrino energy we fix the target of the incident $\nu_\tau$ to be either hydrogen-1 or oxygen-16. For this study, we consider the default G18_02a_00_000 tune.

### 2.1 GEANT

Once we have our neutrino events from GENIE, we can then propagate them into our GEANT4 simulation.Here we define a simple cube ice-model of hydrogen and oxygen, whose dimensions can be determined (nominally this is set to be greater than 30 m × 20 m × 300 m). In order to extend

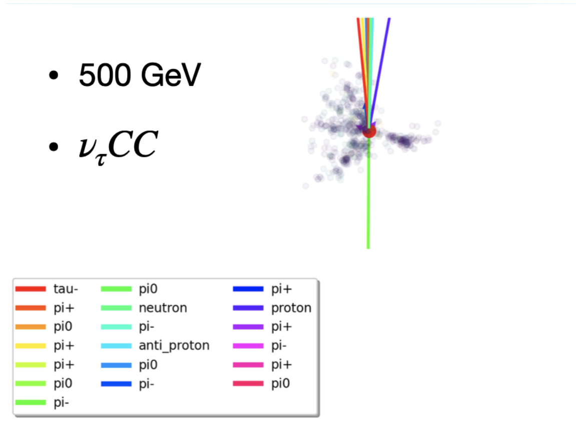


**Figure 2:** Example of a 3D event display for a 500 GeV $\nu_\tau CC$ interaction of an ice-molecule. the bottom green line depicts the direction of the incident up-going neutrino, which is forced to interact at the position depicted by the red circle. Subsequent daughter particles are produced via deep inelastic scattering, as shown in the table. The translucent dots depict the positions of the neutron captures from such an event.

our model to allow for high energy neutrons and low energy neutron propagation below 20 MeV, we utilise the `FTFP_BERT_HP` physics list.

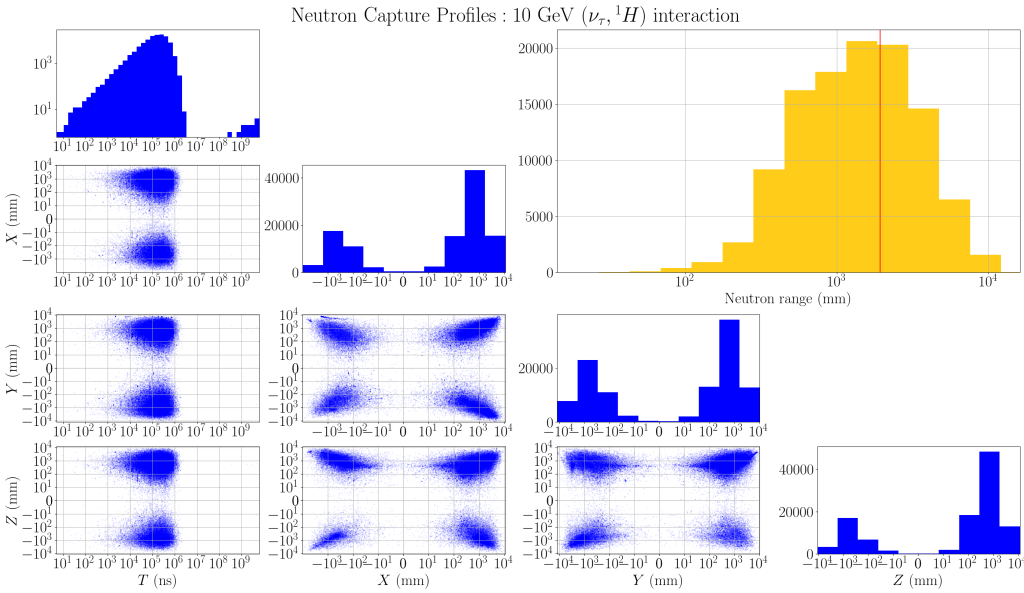


**Figure 3:** Distribution of neutron spatial and timing distributions after 10 GeV $\nu_\tau$ interactions with hydrogen-1 in blue. Yellow shows a histogram of the neutron ranges relative to the primary neutrino vertex with its mean value defined by the red line.

The key parameters in this analysis are the capture timings and as well as the position of the neutrons, multiplicities and kinematical parameters of the neutron captures as a function of incident neutrino energy. Figure 3 and 4 shows an example for the spatial and temporal profiles for 10 GeV $\nu_\tau$ interactions on both hydrogen and oxygen. We find from simulation that in events particularly

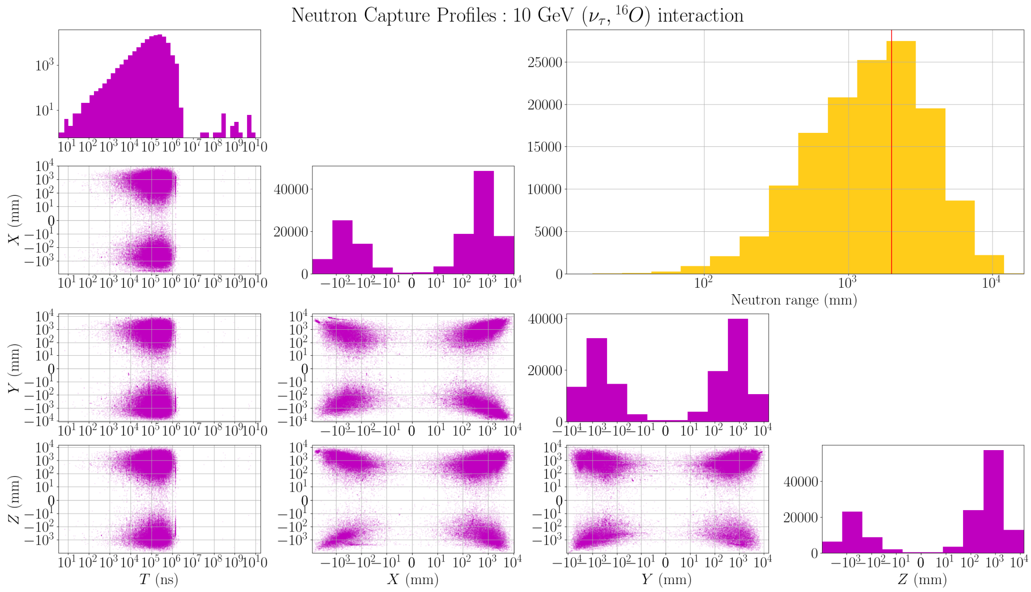


**Figure 4:** Distribution of neutron spatial and timing distributions after 10 GeV $\nu_\tau$ interactions with oxygen-16. Yellow shows a histogram of the neutron ranges relative to the primary neutrino vertex with its mean value defined by the red line.

above the few GeV range, many neutrons propagate to tend to capture in directions approximately perpendicular to the direction of both the neutrino as well as its the outgoing secondaries for the interaction. One expects that this Jacobian-peak feature will be smeared out both due to finite detector resolution, as well as the isotropic emission of 2.23 MeV gammas from neutron captures at rest in the ice. The neutron multiplicities are also shown in Figure 5.

## 3. Future Prospects and Improvements

Future ice Cherenkov detectors offer the possibility to identify astrophysical $\nu_\tau$ events in the sub-TeV range by considering unique signatures given by late light pulses due to neutron captures. By identifying the characteristic Cherenkov light signals associated with neutron captures, this work will determine whether searches for neutron echos will be able to discriminate $\nu_\tau$ events from background signals and other neutrino flavors in future. Here we report simulated neutron captures, characterising their timing and spatial distributions, as well as their multiplicities following neutrino interactions in ice. By focusing on the detection and analysis of neutron capture events, the neutron echo technique enhances the sensitivity to $\nu_\tau$ interactions, improving the ability to differentiate them from background noise and other neutrino flavors. This technique offers a complementary approach to the traditional methods used in Cherenkov-based neutrino detectors. Overall, the neutron echo technique may provide a fruitful method to improve the detection, identification, and characterization of $\nu_\tau$ interactions in next generation ice-Cherenkov detectors, enhancing our understanding of neutrino oscillations, astrophysical sources, and the fundamental properties of neutrinos.

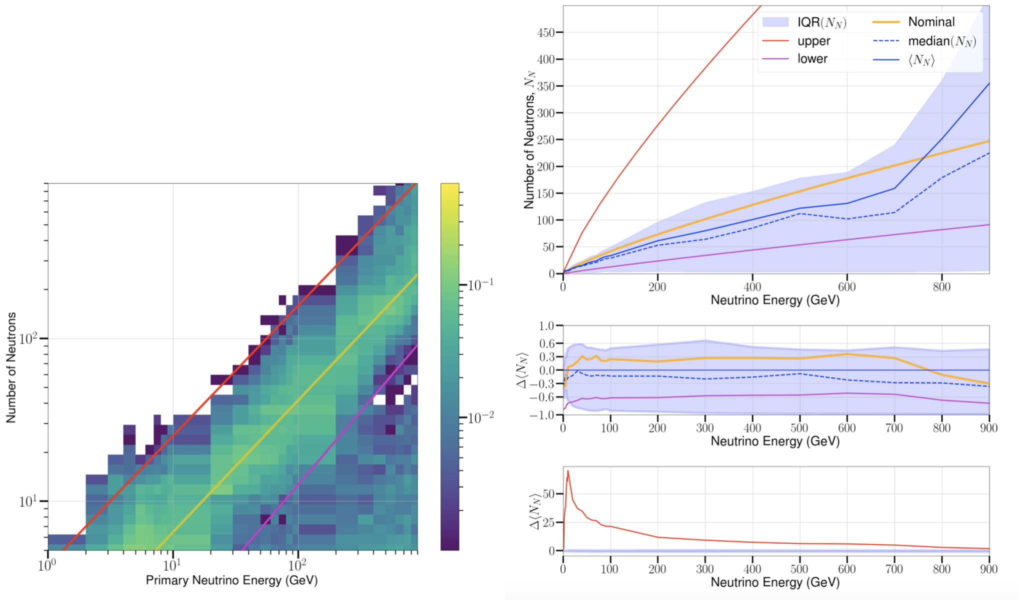


**Figure 5:** Left shows histogram of the simulated number of neutrons for both oxygen and hydrogen targets as a function of primary neutrino energy. Yellow line shows a simple log fit to the neutron yield per incident neutrino energy, $N_N(E_\nu) = (E_\nu/\text{GeV})^{0.81}$. Right shows comparison between the mean neutron yield $\langle N_N(E_\nu)\rangle$, shown by the blue solid line.

## References

[1] **IceCube Collaboration** Collaboration, R. Abbasi *et al.* *Phys. Rev. D* **104** (Jul, 2021) 022002.

[2] K. Fang, J. S. Gallagher, and F. Halzen *The Astrophysical Journal* **933** no. 2, (Jul, 2022) 190.

[3] H. Abreu *et al.* *The European Physical Journal C* **80** no. 1, (Jan, 2020) .

[4] R. Mammen Abraham *et al.* *J. Phys. G* **49** no. 11, (2022) 110501.

[5] **IceCube** Collaboration, R. Abbasi *et al.* *Eur. Phys. J. C* **82** no. 11, (2022) 1031.

[6] S. W. Li, M. Bustamante, and J. F. Beacom *Phys. Rev. Lett.* **122** (Apr, 2019) 151101.

[7] **Particle Data Group** Collaboration, R. L. Workman *et al.* *PTEP* **2022** (2022) 083C01.

[8] C. Andreopoulos *et al.* *Nucl. Instrum. Meth. A* **614** (2010) 87–104.

[9] **GEANT4** Collaboration, S. Agostinelli *et al.* *Nucl. Instrum. Meth. A* **506** (2003) 250–303.