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Identification of neutrino flavor in the ANITA experiment

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Abstract: The ANITA (Antarctic Impulsive Transient Antenna) experiment may be the first experiment to identify astrophysical neutrinos of energy greater than 10^{18} eV. A Monte Carlo simulation has been developed to determine the sensitivity and improve the event reconstruction capabilities of ANITA at energies up to 10^{21} eV. Charged leptons created in charged current neutrino-nucleon interactions can produce secondary showers when they experience hard energy losses through bremsstrahlung, pair production, and photonuclear interactions as they propagate through the ice. Because the cross sections of these interactions depend on the flavor and energy of the charged lepton, the distribution of the showers can indicate the flavor and energy of the neutrino. Results from the simulation are presented.

Introduction

Cosmic ray nucleons with energy greater than $\sim 10^{20}$ eV are expected to lose energy through photopion interactions as they collide with photons of the cosmic microwave background [1]. The charged pions created in these interactions decay to produce neutrinos that can then propagate relatively unattenuated across intergalactic space [2]. The flux density of these GZK neutrinos is predicted to be between 10^{-7} and 10^{-6} km^{-2} s^{-1} sr^{-1} for energies between 10^{19} and 10^{20} eV [3, 4, 5]. Because of the small GZK neutrino flux and the small neutrino-nucleon cross section, a GZK neutrino detector must have an effective volume $\gtrsim 100$ km^3.

The Antarctic Impulsive Transient Antenna (ANITA) experiment is designed to detect neutrinos indirectly through particle showers produced in the Antarctic ice. When a neutrino interacts with a quark, an average of about 21% of its energy is transferred to the quark [6]. What would be an isolated quark and a broken nucleon immediately hadronize to produce mesons that start a hadronic shower in the ice. Some of the particles in the electromagnetic (EM) component of the shower scatter off atomic electrons in the ice, which results in the shower having more electrons than positrons [7]. The pulses of Cherenkov light produced by the extra electrons add coherently at wavelengths greater than the radius of the shower, which is about 10 cm in ice. Antennas hanging from a balloon 36 km above Antarctica can detect radio Cherenkov pulses that imply neutrino events.

If a neutrino-nucleon interaction is charged current (CC), the charged lepton can produce extra showers in the ice. If a $\tau^{\pm}$ experiences a hard photonuclear interaction, the transferred energy becomes a hadronic shower. The photonuclear cross section for a $\mu^{\pm}$ is larger than for a $\tau^{\pm}$, so the hadronic showers produced by a $\mu^{\pm}$ will typically be closer together. A $\mu^{\pm}$ can produce a similar number of EM showers through hard bremsstrahlung and hard pair production. For an electron, the cross sections are large enough for the showers it produces to overlap, resulting in what can seem to be a single long shower with more than one peak [8]. The number of showers and the average distance between showers for an event can help to determine the energy and flavor of the neutrino.

A Monte Carlo simulation of ANITA has been produced to determine the number of and the distance between detectable Cherenkov pulses.

Algorithm

The energy and flavor of a neutrino can be chosen by the user or from a GZK model. If a GZK model is used, the flavor distribution is found by assuming mixing angles of $34°$, $45°$, and $0°$. The nadir angle, free path, interaction type (CC or neutral current (NC)), and energy transfer are chosen randomly from their appropriate distributions. The neutrino then advances to the interaction point and loses some of its energy into a hadronic shower. During lepton propagation, the Earth model is just the Preliminary Earth Model [9] surrounded by an ice shell.

If the interaction is NC, a new free path, interaction type, and energy transfer are chosen and neutrino propagation continues. If a $\nu_{\rm e}$ experiences a CC interaction, the electron induces an EM shower. If a ν_μ or ν_τ experiences a CC interaction, the $\mu^{\pm}$ or $\tau^{\pm}$ usually propagates a distance greater than a shower length before it induces a shower. The propagation of charged leptons is assisted by subroutines taken from MUM [10, 11] and MMC [12]. A free path for relative energy transfer greater than $V_{\rm min} \approx 0.001$ is chosen. As the charged lepton moves to the interaction point, it experiences a continuous energy loss calculated from the integral of relative energy transfers less than $V_{\rm min}$. A $\tau^{\pm}$ has a small chance to decay or experience a CC or NC interaction before it has a chance to propagate the entire free path for a hard energy loss. After the charged lepton reaches the hard interaction point, the interaction type (bremsstrahlung, pair production, or photonuclear) and the energy transfer are chosen randomly from their appropriate distributions. Pair production induces an EM shower and a photonuclear interaction induces a hadronic shower. Bremsstrahlung creates a photon that propagates without energy loss until it reaches the interaction point for either pair production or a photonuclear interaction.

If a shower occurs in the ice shell, the shower's depth, direction, type (EM or hadronic), and energy are recorded along with the relevant properties of the neutrino. The first stage of the simulation ends when all particles have left the Earth or have energy less than $10^{17.4}$ eV.

The second stage of the simulation is based on an early version of another ANITA Monte Carlo [13]. The Earth model is built by plugging the Antarctic Bedmap [14] into Crust 2.0 [15]. The ANITA flight path can be read in from GPS data for a simulation of the first flight or it can be held at a constant altitude at $80°$ S longitude for a simulation of a future flight. Each shower is forced to occur within the payload's horizon and is given a weight factor equal to the fraction of the Earth's surface seen by the payload. The shower length and pulse strength are calculated from the shower parameters [8, 16]. The path of the Cherenkov light from the shower maximum to the payload is found using Snell's Law to converge on the correct exit point on the surface of the ice. A second path is found for a pulse reflected off the bottom of the ice. The pulse strength is reduced by attenuation, refraction, distance to the payload, and how far the pulse direction is off the Cherenkov angle. A simulation of the payload decides whether a pulse activates the global trigger.

If at least one of the pulses does result in a trigger, all other showers from the same neutrino are evaluated. The direction, polarization, field strength, and arrival time for each detected pulse are recorded along with the relevant properties of the neutrino. The event is given a weight factor equal to one divided by the number of showers that led to a global trigger.

The third stage of the simulation arranges the pulses according to their arrival times and removes any pulse that arrives during dead time. When a global trigger occurs, the waveforms are recorded from 50 ns before the trigger to 50 ns after it. When the waveform window closes, the payload begins to look for a second global trigger. If four triggers occur in a short period of time, the payload becomes unable to detect radio pulses until one of the triggers is reset.

Preliminary results

The simulation was run at 10^{19}, 10^{20}, and 10^{21} eV with a 1:1:1 flavor ratio along the first flight path using just the Ronne and Ross ice shelves as the target. Figure 1 shows the distribution of the number of pulses detected in an event for each energy. The percentage of events that were multiple bangs was 17 $\pm$ 2% at 10^{21} eV, 12 $\pm$ 1% at 10^{20} eV, and 4.2 $\pm$ 0.4% at 10^{19} eV. At those same energies, the percentages of multiple bang events that had more than two pulses were 45 $\pm$ 7%, 35 $\pm$ 6%, and 11 $\pm$ 3%. The distribution of the number of pulses per event can therefore give a rough estimate of the neutrino spectrum.

If the neutrino energy can be found using a different method, the number of multiple bang events can indicate the flavor ratio because there were $\sim$ 12 multiple bang events from the ν_μ + ν_τ flux for every multiple bang event from the ν_e flux at all three energies. If the ν_e flux is much greater than half the ν_μ + ν_τ flux, the number of single bang events for every multiple bang event will be greater than what is expected.

The flavor ratio can also be found from the average time separating the pulses of a multiple bang event. The pulses from ν_e double bangs are typically separated by 400 - 3000 ns. The ν_μ produce most of the multiple bangs with average separation times $\lesssim$ 100 ns. Beyond about 1000 ns, the distribution of separation times for ν_μ matches the neutral current-based double bangs seen from ν_e. The ν_τ are more likely than ν_μ to produce multiple bangs with average separation times greater than 400 ns. The distribution of separation times at 10^{20} eV is shown in figure 2 for each flavor. The result was about the same at 10^{19} and 10^{21} eV.

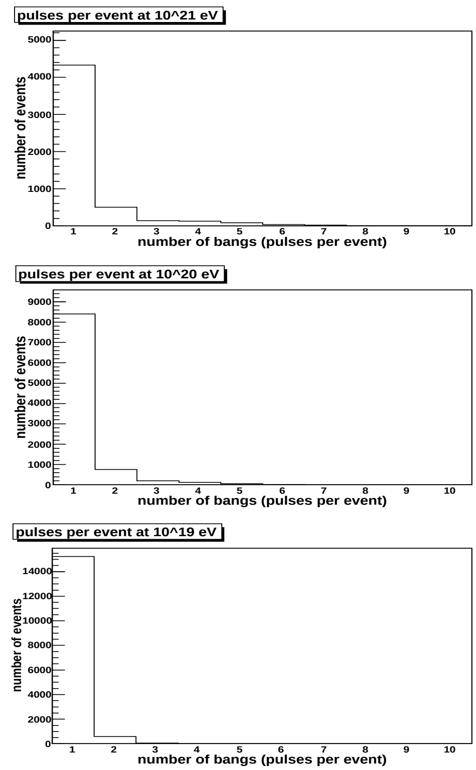

Figure 1: distribution of the number of pulses per event at 10^{21} (top), 10^{20} (middle), and 10^{19} eV (bottom)

Conclusion

The energy and flavor of ultra-high energy cosmic ray neutrinos can be determined in part from the number and separation of pulses detected by ANITA in multiple bang events. If ANITA detects a large number of events, the number of multiple

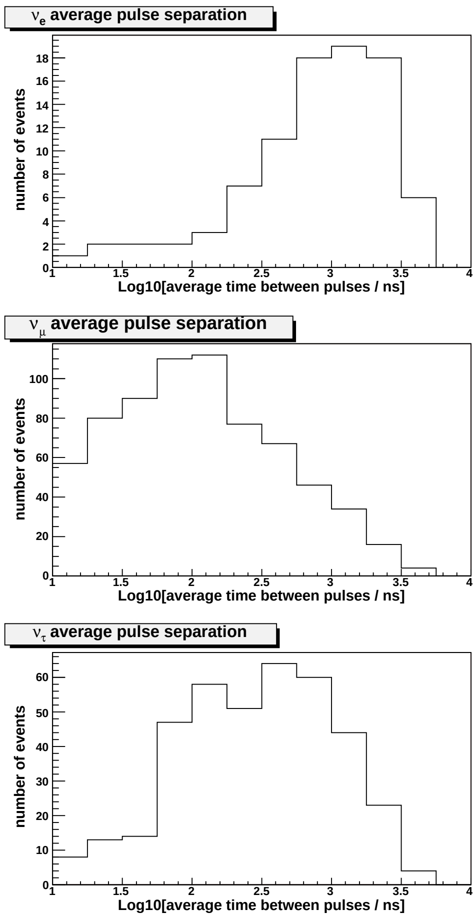

Figure 2: distribution of the average amount of time separating the pulses of a multiple bang event at 10^{20} eV. top: ν_e, middle: ν_μ, bottom: ν_τ

bang events can indicate the spectrum and flavor distribution of the neutrino flux.

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