Radio detection of ultra high energy neutrinos

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Abstract

Recent evidence for observation of the Greisen–Zatsepin–Kuzmin (GZK) cutoff in the cosmic ray spectrum has a number of profound implications for our understanding of high energy astroparticle physics. This GZK process itself produces neutrinos that are strongly believed to be both spectrally and spatially correlated to high energy cosmic ray particles above 100 EeV. In the 1960’s Askaryan predicted that spatially compact nature of electromagnetic showers produced from the interaction of such high energy neutrinos would lead to coherent Cherenkov radiation. In June 2006 these Askaryan effect predictions were verified for emulated EeV showers in a 7 ton ice target at SLAC. A number of current and future experiments are now actively exploiting this radio detection method to search for the “guaranteed” GZK flux of high energy neutrinos. None have yet been observed, though the sensitivity of the detectors is just now approaching the predicted range. The ANtarctic Impulsive Transient Antenna (ANITA) experiment, a long-duration balloon operating at an altitude of 37 km, flew for over a month during December 2006–January 2007, and again December 2008–January 2009. In the longer term, a large-scale terrestrial radio array opens the possibility to probe deep inelastic neutrino-nucleon scattering at center of mass energies well above those of any proposed future collider. Prototype instrumentation stations have been evaluated. Essential to the realization of these experiments has been the development of affordable instrumentation with adequate radio frequency performance.

1. Introduction

Recent observations [1] from the Pierre Auger observatory support an extra-galactic origin to the highest energy cosmic ray events, whose acceleration mechanism is not understood [2]. Protons of this energy cannot travel very far through the cosmic microwave background without interacting, which means they should be produced nearby. Paradoxically, there is little evidence for nearby point sources.

Degradation of the flux of these ultra high energy (UHE) protons was first pointed out by Greisen, Zatsepin and Kuzmin (GZK) [3] via the process:

\[ p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \]  \hspace{1cm} (1)

where the subsequent \( \pi^+ \) decay chain leads to a flux of high energy neutrinos—denoted the GZK \( \nu \) flux. Based upon the cosmic ray flux observed, and assumptions about source distance and evolution, predictions for the flux can be made. While the number of these neutrinos is large, their small cross-section requires a large instrumented volume. Existing detectors are simply too small.

When completed, latest-generation enormous detectors, such as the Pierre Auger observatory [4] and the IceCube array [5], will start to have possible sensitivity to these events at the one-per-year level. Given the cost of these detectors, they are unlikely to significantly scale up in size using the same detection techniques. Unambiguous observation of these GZK neutrinos requires a new approach, and radio detection is a promising candidate.

2. Coherent radio detection

When neutrinos of very high energy interact in solid matter, the development of the subsequent shower progresses with electrons being Compton scattered into the shower, while positrons annihilate. This leads to a net 20–30% negative charge excess [6,7]. Such a shower was predicted to have the following remarkable properties:

- would develop a local, relativistic net negative charge excess,
- would be coherent (\( P_{\text{ch}} \sim E^2 \)) for radio frequencies,
- intensity can be well above thermal noise for UHE neutrinos,
- would have a net negative charge excess of a few muons.

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can be detectable at a distance (via antennas),
would be polarized—can determine the location on Cherenkov cone with a single-point measurement,
which have been experimentally verified for potential target materials (ice, salt, sand) in recent years [8,9].

3. The Antarctic impulsive transient antenna

While a number of experiments have been operated based upon radio detection [10,12,11], their sensitivity was far from that needed to detect the predicted GZK $\nu$ flux. The ANITA experiment was designed specifically to be the first to measure—or unambiguously challenge—the predicted (“guaranteed”) flux of GZK neutrinos. In order to do so, the entire Antarctic ice sheet is used as a target volume, as sketched in Fig. 1. Fig. 2 depicts the ANITA payload [13,14] for first flight, where the key functional components are indicated.

To meet the severe low-power requirements, enabling advances were made in RF triggering [15] and RF transient waveform recording [16] for a large number of channels. During a 35-day flight over 7M events were recorded, and neutrino flux limits reported [17,18].

Experience from the first flight led to a fine-tuning of the trigger hardware and firmware, and the signal processing chain is shown schematically in Fig. 3. RF signals are split into a trigger processing path and a waveform recording path, and all triggering and digitization is performed inside a custom 21-slot conduction-cooled cPCI crate.

Concerted calibration efforts were able to reduce the timing jitter within and between digitizer (“SURF”) cards to 16 and 32 ps, respectively. This allows measurement of RF impulsive signal arrival directions to about $0.2^\circ\pm0.1^\circ$ in elevation (azimuth), providing excellent event position reconstruction. A second Antarctic flight was successfully completed in January 2009. Over 26 million triggered events were recorded during a more favorable flight path (more cold, deep ice and less anthropogenic noise) and analysis of the results will be reported later.

4. Tera-ton scale detectors

The low duty-cycle and limited aperture of an ANITA-type detector are fundamental constraints. To go beyond the discovery level of a few GZK neutrinos and start to do physics and astronomy with these vs, a large, embedded array is envisioned. An instrumented volume many hundreds of km$^3$ water equivalent is estimated as a minimum target size needed based upon current flux limits. The use of salt and ice as target media are currently being studied, where in each case the development of affordable and high-performance RF electronics is crucial.
4.1. Salt dome shower array [SalSA]

Naturally occurring salt domes are an attractive choice for a detector medium [19] due to their relative ease of access and extensive study by the petroleum industry. Salt, being 2.4 times denser than ice, provides a correspondingly larger target water equivalent for the same instrumented volume. The SalSA collaboration [20] has studied the feasibility of the detector concept illustrated in Fig. 4. A prototype readout station [21] has been fabricated and demonstrated the viability of the technique reported.

There remain concerns about uniformity, attenuation length, and drilling costs. Moreover, once a given dome is completely instrumented, the target volume saturates.

4.2. Icecube radio array [IceRay]

Radio extensions to the IceCube detector are a cost-effective means to expand the instrumented volume. A few prototype modules [22], utilizing the existing IceCube infrastructure, have been installed for evaluation, employing the RF triggering and recording infrastructure developed by ANITA. A concept for expanding this to a much larger array, one variant of which is depicted in Fig. 5, is being pursued by the IceRay collaboration [23]. Shown on the left is a “hybrid” event where the strengths of the composite detector elements have synergy: radio tagging of the neutrino event and optical energy determination.

Each station can be thought of as a small, embedded ANITA experiment. Continued advances in waveform sampling [24], in particular IceRay-size sampling depth extensions for sub-trigger threshold recording, show promise for enhanced neutrino flavor identification. It is ready for deployment in Austral summer 2009–2010.

References