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Feasibility of antenna array experiment for Earth skimming tau-neutrino detection in Antarctica

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The radio technique has attracted attention as a next generation method for detection of astrophysical ultra-high energy neutrinos, and has continued to develop through experiments such as RICE, ANITA, ARIANNA, and ARA in Antarctica over the past a couple of decades. In this paper, we propose a new radio antenna array experiment dedicated to the detection of tau-neutrinos emerging from the nearby mountains which detects radio impulses produced from tau decay showers as result of its interaction with the geomagnetic field. Because of the presence of strong magnetic fields required for the production of the signal as well as low level of anthropogenic radio noise, the area around the Transantarctic Mountains in Antarctica is considered as the most suitable place for the experiment. A prototype station was successfully deployed at Moore's Bay in Antarctica during December 2016, took data for several months. We describe the physics motivation, the design of instrumentation, projected sensitivity, as well as overview of data taken by the prototype station.

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1. Introduction

Since the first discovery of IceCube [1], we have met an exciting new era that could be used as a probe to study the universe. However, in order to detect GZK neutrinos [2,3], which are expected to be predominantly present in energies higher than 10^{18} eV, it is required to obtain at least an order of magnitude higher target volume than IceCube. As a plausible solution to this, the radio technique has begun to attract attention, has continued to develop through many experiments such as RICE, ANITA, ARA and ARIANNA [4,5,6,7].

All of these experiments employ a method that detects impulsive radio pulses produced through a process, called so-called Askaryan effect, in the development of a shower induced by neutrino interactions. With a great evolution of Radio Frequency (RF) technology over recent decades, the devices required for RF detection has become cost effective, and Askaryan's genius proposal in the 1960s became a realistic experimental methodology since the late 2000s. Taking an advantage of a radio-transparent characteristic in the cold Antarctic ice with long attenuation length in the order of km, they can effectively obtain the target volume to study of the GZK neutrinos.

However, these experiments based on the Askaryan effect have a disadvantage that the flavor identification of neutrinos is difficult. Unlike IceCube, which is able to distinguish between muon (or tau) with an excellent tracking capability using a dense optical sensor array, all radio signals detected on the antenna are almost identical, regardless of neutrino flavors or whether the neutrino interaction is CC or NC.

On the other hand, the upcoming event found by the recently reported ANITA [8] is very interesting. ANITA has demonstrated that it can detect radio pulse from an extensive air shower (EAS) in the Antarctica [9], which is produced by a synchrotron-like process; the relativistic charged particles in EAS produce coherent emission as a result of deflections in the geomagnetic field. Majority among the 20 EAS events detected by ANITA are down-going signals reflected off from the ice surface and 3 events are atmospheric-skimming events near the horizon. They can be distinguished not only seeing the arrival direction of the radio signal but also the polarity inverse which is a strong evidence of the reflection. However, the interesting event recently reported by ANITA shows that the arrival direction is up-coming but does not show the polarity inverse characteristics, suggesting that it may be caused by an up-coming shower rather than the down-going UHE. Despite of that it is controversial, because the statistics are critically insufficient (only single event detected) and the Earth passing distance which corresponds to the arrival directions of the event cannot accounted for in the cross-section predicted by the standard model, it is important to note that it has opened a new way of detecting tau neutrinos.

Our approach is conceptually the same as ANITA’s method for the up-coming shower; detecting the impulsive radio signals from the in-air hadronic showers through the decay of tau emerged from the tau neutrinos. However, instead of using balloons at high altitudes, we place antennas on the ground and point at the high mountains to detect the mountain skimming neutrinos. Figure 1 illustrates our detection concept.

We note the greatest attraction that this experiment is dedicated for the tau neutrinos. In the ultra-high energy, only tau can escape through the rock in the mountain after the neutrino interaction and decays in the air, so there is no need for a flavor identification which is the difficulty in other radio experiments. Since we can only detect the tau out of the three flavors, it one can point out that there is a disadvantage that the flux is reduced to one-third. However, when the flux of the tau neutrinos delivered from this experiment is studied with a total flux obtained from other experiments, a precise measurement of the neutrino flavor ratios will be a sharp probe to understand on many excellent physics topics such as the neutrino source, neutrino oscillation, neutrino decay, and the mass hierarchy [10].

An accurate pointing resolution of the neutrino arrival direction is also a major advantage in this experiment. The Askaryan signal in the cold ice forms a wide Cherenkov cone of about 56 degrees which introduces an inevitable ambiguity in determining the direction of the detected neutrinos. On the other hand, since the radio signal from the tau shower is shaped like a pencil beam (the Cherenkov angle in air is less than 1.5 degrees), the pointing resolution in our experiment is intrinsically excellent, which is crucially helpful for point source search.

In fact, the detection of the mountain skimming tau neutrino has been proposed for a long time, but mainly in experiments based on the optical signal detection [11]; For instance, the lowest limit obtained by PAO in the energy band of the GZK neutrinos was also based on this method [12]. On the other hand, we use the radio technique which can realize a cost effective experiment instead of using high-cost optical equipment. The radio method has another great advantage of being able to achieve almost 100% of the lowest duty cycle, which is the most vulnerable to the optical based experiments.

Our ground based approach can provide a long exposure which is limited in balloon based experiments due to limited flight time. Furthermore, by placing the antennas close to the showers in front of the mountain, we can reduce the $1/r^2$ propagation loss, and therefore can lower the energy threshold than the balloon experiment, and utilize it in the GZK energy band.

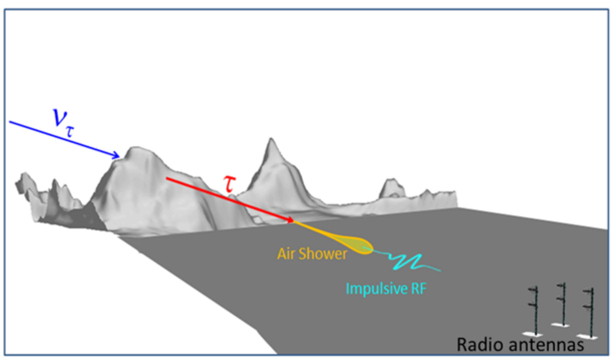

Figure 1. Concept of the tau neutrino detection via radio.

2. Tau-neutrino detection in Antarctica

ANITA's observation of EAS has brought valuable lessons. First, while other radio-based EAS experiments use low frequencies below 100 MHz, ANITA has proved the strong emissions even at high frequencies above 200 MHz where the Galactic noise is relatively low. This has influenced our experimental design which uses a relatively small antennas designed for the high frequencies. It provides a practical way to create a large scale antenna array by simplifying the antenna support structure and making installation easier. ANITA also proved that Antarctica is the excellent place for the experiment, where the ambient anthropogenic noise is the quietest and has the strongest geo-magnetic field required for the geo-synchrotron radiation. Noting that there are many high mountains in Antarctica, we concluded that Antarctica, especially the vicinity of Transantarctic Mountains is the best place for this experiment.

The figure 2 shows an example of a station that constitutes a radio array that we propose. A single station consists of several dual polarization antennas, which allows a complete set of measurements including 1) the magnitude of the pulse related the energy of the shower, 2) the RF arrival direction which almost coincides with the direction of the original neutrino, 3) the polarization which is to be the linearly polarized, and 4) the polarization angle to be the same as the geomagnetic field.

An array can be implemented by installing multiple stations in appropriate spacing over a large area. Each station operates independently, so a complicated trigger system including communication between the stations is not required. Multi-station coincidence events can be selected using the time stamp information on offline analysis. This standalone station approach is similar to the TAROGE experiment [13], but different from the GRAND experiment [14].

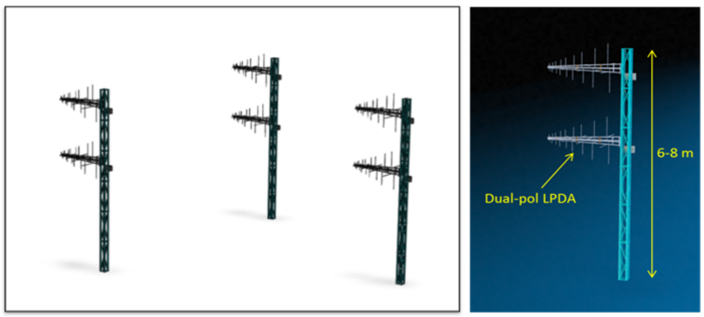

Figure 2. A radio station for Tau-neutrino detection.

The antenna design we are considering is a dual-polarization log-periodic antenna array (LPDA) which has an excellent response in wideband. LPDA is light weight and could withstand the harsh environment of Antarctica with strong winds.The again of antenna of 7-8 dBi is achievable in 120-500 MHz with the boom length of 1.5-2 m.

The number of antennas per station and the antenna allocation will be determined through further studies. As an initial design of the station, we propose a total 6 dual-polarization LPDAs installed in three towers. The arrival direction of RF can be reconstructed by the interferometry technique, where the baseline between the antennas is an important parameter together with the time resolution of the system. It is desirable to increase the spacing between the towers for a precise azimuth angular resolution. However, the RF transmission characteristic will deteriorate if the too long RF cables are accompany with, so the towers would be located preferably within a radius of 10m. It is important to have good elevation angular resolution because the way to distinguish tau neutrinos from cosmic rays is to determine whether the arrival direction is associated with mountains. Therefore, longer vertical spacing is desired, but it would be 3-4m in practices. Considering the tau decay length and the distance reach to the shower maximum, the distance between the mountain and the station should be several tens of kilometers. From that distance, the height of Transantarctic Mountain (2-3 km) will be below 10 degrees, so antennas with a narrow beam pattern in the vertical direction is preferred. On the other hand, a wide beam pattern is needed in the horizontal direction to increase acceptance. This requirement can be implemented by various designs, for examples stacking multiple LPDAs. The phased summation of the signals of antennas along the vertical direction can be considered, which will drastically improve system response in a narrow vertical angle.

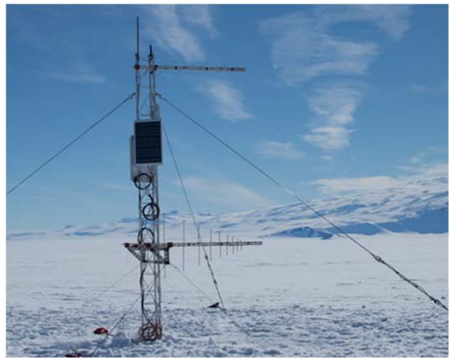

Figure 3. ARIANNA-HCR Station (December 2016, credit C. Persichilli).

3. Prototype station

Together with the ARIANNA collaboration, we successfully installed a prototype station (ARIANNA-HCR) in Moore's bay, Antarctica in the summer season of Austral in 2016. There are two high mountains around the site, Mount. Discovery (2,681 m) and Mt. Morning (2,725). ARIANNA-HCR with four LPDA antennas (3 for horizontal polarization and 1 for vertical polarization) installed on one tower (see figure 3), had several goals such as an evaluation of construction/robustness, a long-term RFI survey, an evaluation of angular reconstruction and its resolution, studies on cosmic ray backgrounds, and possible measurements of cosmic ray fluxes in various elevation angles. The station operated successfully during the Austral summer. More details will be discussed in the other presentation in this conference [15].

4. Simulation Study

We performed a Monte-Carlo simulation study in order to estimate the sensitivity of the experiment. A software package, Simulation of High-energy Neutrinos Interaction with the Earth (SHINIE), was used to simulate neutrino interaction and tau propagation in rock. The neutrino interaction model is based on the CTEQ6 Parton distribution, and takes into account for both the charged current (CC) and the neutral current (NC). The tau propagation includes energy losses via the pair production, the photo-nuclear interaction, the ionization, and bremsstrahlung. The tau regeneration is also taken into account. We use a realistic model of terrain around Moore's bay based on data from the Radarsat Antarctic Mapping Project [17]. We consider the uniform density (2.65g/cm^3) of rock under the surface. Figure 4 shows distributions of energies and flight distances of the emerging tau leptons for various energies of incident neutrinos. Here, the flight distance is from the emerging point of the tau to the decay point. We define the conversion factor as a ratio of number of tau leptons to the incident neutrinos, and figure 5 shows distributions of the conversion factors vs. neutrino energies for various penetrating depths.

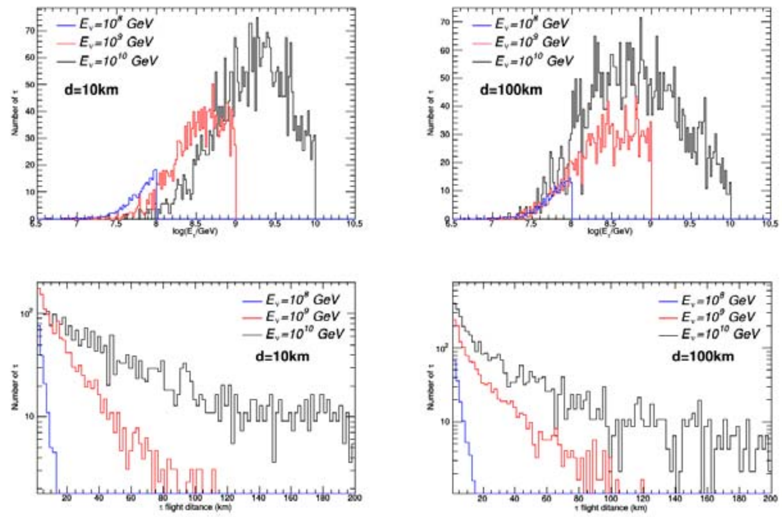

Figure 4. Energy distributions of the emerging tau leptons (top) and flight distances (bottom). Left figures are for 10km of mountain penentrating depth, and right figures for 100km.

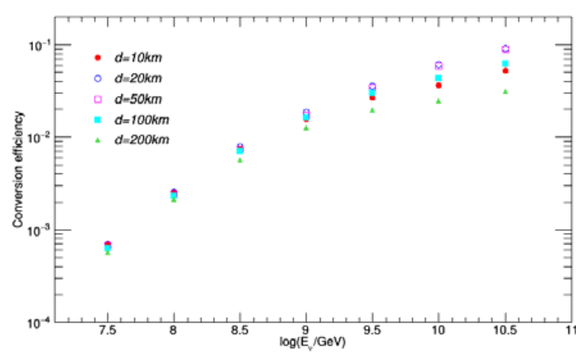

Figure 5. Conversion factor distribution vs. neutrino energies.

For the tau decay in air, we consider 8 decay modes which have highest branching fractions. Assuming that all secondary electrons, positrons, and pions contribute to the development of the air-shower, we define the shower energy, E_{shower} as their energy sum. Here, the energy loss and decay of muon are not considered. Figure 6 (left) shows E_{shower} distributions for various neutrino energies.

Instead of doing detailed simulations of the radio emission and propagation, we use a simple method to exam if a given event can be detected. We define the observed energy at the receiver, E_{obs} as follows

$$E_{obs} = \frac{E_{shower}}{L_{RF}},$$

where the L_{RF} is RF propagation length from the shower maximum to the receiver, and compare it with the threshold. We assume the same system response and noise as ANITA-I except the antenna gain. The threshold of ANITA-I, $E_{thr}^{ANITA} = 7 \times 10^6$GeV/km, was found by compiling information of ANITA's cosmic ray events [18], which includes energies, RF propagation lengths, and reflection coefficients. Our threshold can be obtained by taking into account antenna gains,

$$E_{thr} = E_{thr}^{ANITA} \times 10^{(G_{ANITA}-G)/20}.$$

Here, G_{ANITA} and G are antenna gains in dBi for ANITA (10 dBi) and our system, respectively. Figure 6 (right) shows E_{obs} distributions for various neutrino energies. The arrows in the figure indicate threshold values for two configurations of the antenna gains (7 dBi and 10 dBi).

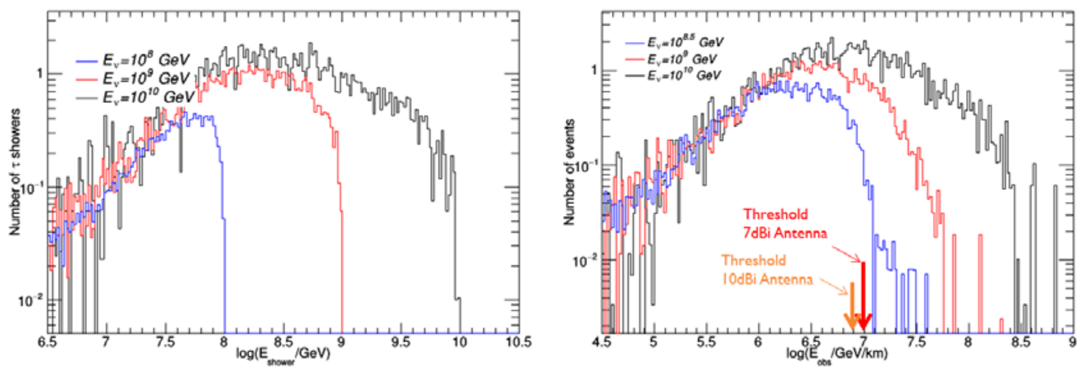

Figure 6. Distributions of the E_{shower} *(left) and the* E_{obs} *(right).*

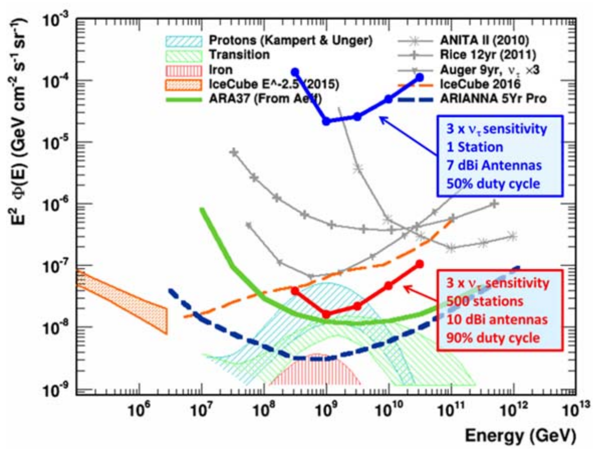

Figure 7. Projected sensitivities.

Figure 7 displays the project neutrino sensitivity of our experiment. The solid curve in blue color shows the projected sensitivity for a single station with 7 dBi antennas and 50% duty cycle which were the similar parameters as ARIANNA-HCR. The sold curve in red is for the full scale array assuming a total 500 stations with 10 dBi antennas and 90% duty cycle. Five years of operation time is assumed for both curves.

5. Conclusion

We propose a new radio antenna array experiment dedicated to the detection of tau-neutrinos in Antarctica, which is utilized to detects radio signals emitted at shower of tau decay shower. This paper described the scientific potential of the proposed experiment, the detection concept and the initial system design. Simulation studies have shown that this experiment is competitive compared to other experiments. More detailed simulation studies will be made in the future, and hardware development including new antennas will be continued. The ARIANNA-HCR was installed as a prototype station, and operated successfully. More details on the ARIANNA-HCR were given in the other report in this conference.

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References

[1] M. G. Aartsen et al., Science Vol. 342, Issue 6161, 1242856 (2013)

[2] K. Greisen, Phys. Rev Lett. 16,748 (1966)

[3] G.T. Zatsepin and V. A. Kuzmin, JETP Letters 4, 78 (1966)

[4] I. Kravchenko et al. Phys. Rev. D 85, 062004 (2012)

[5] P. Gorham et al., Phy. Rev. Lett. 103, 051103 (2009)

[6] P. Allison et al., Astroparticle Physics, Vol. 35, Issue 7, 457-477 (2012)

[7] S. W. Barwick et al., Astroparticle Physics, 70, 12-26 (2015)

[8] P.W. Gorham, et al., Phys. Rev. Lett. 117, 071101 (2016)

[9] S. Hoover et al., Phys. Rev. Lett. 105, 151101 (2010)

[10] S. Wang et al., J. of Cosmology and Astroparticle Phys. Vol. 2013 (2013)

[11] W. S. Hou. et al., J. of Phys. Soc. of Japan, Vol. 77, issue Suppl. B, 76-78 (2008)

[12] P. Abreu et al., Adv. In High Energy Phys. Vol. 2013 708680 (2013)

[13] J. W. Nam et al, Int. J. Mod. Phys. D 25, 1645013 (2016)

[14] O. Martineau-Huynh et al., EPJ Web of Conference 116, 03005 (2016)

[15] S. Wang et al., presentation in ICRC2017 (2017)

[16] M.A. Huang et al. Nucl. Phys. B (proc. supl.) Vol. 175–176, 472–475

[17] Liu, H., K. Jezek, B. Li, and Z. Zhao. 2001. *Radarsat Antarctic Mapping Project Digital Elevation Model, Version 2*. 400m RAMP DEM data set. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. [Date accessed in Dec 2016].

[18] H. Schoorlemmer et al., Astroparticle Physics, 77, 32-43 (2016)