On ANITA’s sensitivity to long-lived, charged massive particles

Amy Connolly, Patrick Allison, Oindree Banerjee

Dept. of Physics, Center for Cosmology and AstroParticle Physics, Ohio State Univ., Columbus, OH 43210.

Abstract

We propose that the Antarctic Impulsive Transient Antenna (ANITA) can serve as a detector for long-lived, charged particles, through its measurement of extensive air showers from secondary leptons. To test this on an example model, we simulate the production of staus inside the earth from interactions between ultra-high energy neutrinos and nuclei. We propose that results of ANITA searches for upgoing air showers can be interpreted in terms of constraints on long-lived, charged massive particles (CHAMPs) and consider a supersymmetric partner of the tau lepton, the stau, as an example of such a particle. Exploring the parameter space in stau mass and lifetimes, we find that the stau properties that lead to an observable signal in ANITA are highly energy dependent. At $10^{18.5}$ eV, we find that the best constraints on the product of the neutrino flux and the stau production cross section would be placed near $m_{\tilde{\tau}} = 1$ TeV and $\tau_{\tilde{\tau}} = 10$ ns. Thus ANITA could be sensitive to new physics in a region of parameter space that is unconstrained by experiments at the Large Hadron Collider.

Keywords:
nu miser, radio detection, ultra-high-energy, supersymmetry

1. Introduction

ANITA is primarily designed as an ultra-high energy (UHE) neutrino discovery experiment, operating under NASA’s long-duration balloon program [15]. ANITA searches for broadband, impulsive signals at radio frequencies expected from Askaryan radiation produced from neutrino-induced cascades in the ice.

ANITA also serves as a UHE cosmic ray detector [18]. Extensive air showers (EAS) due to cosmic rays produce synchrotron and Askaryan emission in the local, nearly-vertical geomagnetic field, observed by ANITA as horizontally-polarized (HPol) pulses, in contrast to the neutrino signature described above where events are expected to be predominantly vertically-polarized (VPol). ANITA detects these air-shower-induced pulses mainly after their reflection off of the ice, where the signals acquire a polarity opposite from those observed directly. Events observed directly are typically seen at elevation angles above the horizon as seen by ANITA, which is 6.5 degrees down from the horizontal.

Long-lived, charged massive particles (CHAMPs) produced in the earth could be detected by ANITA if they ultimately lead to an observable EAS. Since EAS signals arriving from elevation angles steeper than 6.5 degrees are expected to have obtained an opposite polarity from a reflection, upward-going signals with a non-inverted polarity could be a signature for an association with a CHAMP.

Models that lead to upward-going air showers observable by ANITA have heightened interest with ANITA’s reporting of two upward-going, unusual events [16, 17]. Cherry et al. [11] have proposed a sterile neutrino origin for these events, and Anchordoqui et al. [8] extends this work to accommodate a massive dark matter candidate (480 PeV right-handed neutrino), trapped in the earth, in place of the sterile neutrino. The dark matter particle could decay into a Higgs and a light Majorana neutrino, the latter of which would produce a lepton in the crust causing the observed air shower. Both of these possibilities may have significant problems producing the observed arrival directions at ANITA without overproducing at other angles. Anchordoqui et al. addressed this by evoking an atypical dark matter density distribution in the Earth.

We find that the CHAMPs investigated here would suffer a similar problem if they were to be posed as an explanation of the unusual events reported by ANITA; a preference for steeply upward-going events comes in a region of parameter space with far-less-than-optimal event rates that are not expected to be detectable. Still, we report on the sensitivity of ANITA to CHAMPs coming from any angle as a new search channel for the experiment.

2. CHAMPs and neutrino telescopes

Long-lived, charged particles have long appeared in extensions to the Standard Model (SM) of particle physics. For our investigation we consider a long-lived charged slepton that arise in some supersymmetric models.

Supersymmetry (SUSY) offers a symmetry between bosons and fermions that could offer a solution to the fine-tuning problem that plagues the SM, as well as a possible...
unification of couplings at high energies. Requiring Rparity conservation requires that the Lightest SUSY Particle (LSP) be stable, and depending on the scale, this can be the gravitino. In this case, the Next to Lightest SUSY Particle (NLSP) can be a charged slepton, specifically, the right-handed stau. Moreover, the decay of the stleton can be kinematically suppressed, and thus its lifetime long, if the difference between the masses of the LSP and NLSP is small.

Collider searches have placed lower bounds of about 450 GeV on the mass of a long-lived charged slepton [2, 21, 3, 10] for cases where the particle lives long enough to leave the detector. Direct stau production has been ruled out for masses below about 300 GeV [2]. These bounds are typically based on some model assumptions.

Neutrino observatories have been previously proposed as detectors of long-lived, supersymmetric particles. Albuquerque et al. [6, 7] and Ahlers et al. [4, 5] point out that km$^2$-scale neutrino telescopes could inform the SUSY breaking scale, while complementing results from the Large Hadron Collider (LHC.)

In the studies in [6, 7, 4], UHE neutrinos produce stau pairs through interactions with a nucleon in the earth. The proposed signature for the observation of staus is the detection of two parallel charged tracks separated by about 100 meters predicting at least a few events per year for an optical Cherenkov detector such as IceCube. In [5], they considered cosmic rays rather than neutrinos producing the staus, and [9] considered both cases. It is expected that neutrinos would produce the dominant flux for most typical supersymmetric models, since cosmic rays primarily interact via Standard Model strong interactions [9].

The requirement of a stau pair with nearby parallel tracks in the searches proposed in [6, 7, 4, 5] is motivated by the obstacle of distinguishing between high energy stau and low energy muon tracks as IceCube is particularly susceptible to the latter. However, this strongly limits the detection ability at extremely high energies, where the effective rate can be suppressed by a factor of 1000 or more [20]. In addition, in the model where only one of the supersymmetric particles produced is a stau, the only detection channel open for IceCube would be the rate produced by the stau decay interacted inside the IceCube volume directly. ANITA, on the other hand, does not suffer from the challenges of a muon-dimuon background, so an argument for a single stau detection is conceivable.

3. A preference for shallow upward-going events

Based on purely geometric considerations, and assuming an isotropic incident flux with neutrino interactions turned off, Fig. 1 shows a strong preference for shallow trajectories as seen by ANITA. This is because a particle incident with a steep trajectory from the far side of the earth sees ANITA’s 700 km-radius ice target as covering a small solid angle, while a neutrino arriving at a more shallow angle sees the ice in ANITA’s horizon at a shorter distance. Coming from below, however, ANITA’s target looks like a circle while from a shallow angle it is viewed at an angle, lowering the probability of it being intersected by the particle trajectory.

Roughly, for an isotropic incident flux, the ratio of probabilities that an event arriving at a steep angle emerges within ANITA’s horizon compared to the probability that one at a shallow angle does can then be estimated as:

$$P(\theta_{\text{step}}) \approx \frac{c_{\text{shallow}}^2 \sin \theta_{\text{step}}}{c_{\text{steep}} \sin \theta_{\text{shallow}}}$$  \hspace{1cm} (1)$$

where the $c$’s are the chord lengths traversed by each type of trajectory. If we consider $\theta_{\text{shallow}} = 6.5^\circ$ and $\theta_{\text{step}} = 35^\circ$, then taking the earth radius $R_{\text{earth}} = 6.36 \times 10^6$ m, then $c_{\text{shallow}} = 460$ km and $c_{\text{steep}} = 7200$ km, giving:

$$P(\theta_{\text{step}}) \approx 2\%.$$  \hspace{1cm} (2)$$

As shown in Fig. 1, using a toy Monte Carlo we find the distribution of incident angles for an isotropic flux of completely lossless particles, and find that approximately 1.7% of those would be seen by ANITA to have incident angles greater than 27$^\circ$. However, this includes the uptick near 90$^\circ$ incident angles where ANITA’s ice target is seen straight on as a circle.

If we only consider incident angles in the range 27 – 50$^\circ$ they account for only 0.7% of trajectories that emerge in ANITA’s horizon, and again this does not include neutrino absorption in the earth that would only strongly suppress steep events. We point out that this purely geometric ar-
gument means that any model that is to explain a preference for steep incoming trajectories over shallow ones, if assuming an isotropic neutrino flux, must overcome this bias for shallow trajectories by about a factor of $\sim 100$. We note however, that ANITA does consider point sources as the origin of neutrinos leading to the upward-going events.

We note that the IceCube detector has reported a high-energy, through-going track event with 2.6 PeV deposited energy [26], implying a neutrino flux at about 10 PeV, but upward-going at $\sim 10^5$. As noted in [22], a lack of events at shallower and downward-going angles is interesting, and motivates a mechanism that might preferentially produce steeply upward-going events. It is also worth noting that the Pierre Auger Observatory, the only other similar-scale experiment in this energy range, would likely not be able to observe similar steeply upward-going events with their standard analysis (intended for earth-skimming neutrinos from $\nu N$ interaction, a tau pair could be produced instead, doubling the probability of detection.

4. Modeling upward-going taus enabled by long-lived stau leptons

We wish to estimate the probabilities for neutrinos at different energies to penetrate the earth at different incident angles as seen by ANITA through the signature shown in Fig. 2, that is, single stau production where a tau emerges from the earth and decays in air. For this we utilize both a toy Monte Carlo and a separate integration of the probability that a neutrino will lead to an observable air shower for a given incident angle. We note that stau pair production might also contribute, as would events where a tau decays close enough to the surface for the shower to emerge, but we do not consider either of those at this stage. We consider both an isotropic neutrino flux (arriving from $2\pi$ above the surface at any entrance point), and a single input angle of incidence, and also model both flux spectra and sets of monoenergetic neutrinos.

Our simulation is kept relatively simple at this stage to simplify understanding. At this stage, we give the entire earth the density of the mantle, and we propagate energy losses of both the stau and the tau as described below. At each interaction, the energy of the decay product of interest is just half of its parent’s, so that the initial stau energy is $E_{\text{stau}} = E/2$, the initial tau energy is $E_{\tau} = E_{\text{stau}}/2$, and the energy of the shower produced by the tau is $E_{\text{shower}} = E_{\text{stau}}/2$. We take the threshold for detectability of a shower at ANITA to be $10^{17}$ eV when at 100 km distance, taking the signal strength of any given shower to be proportional to energy and inversely proportional to distance. A more thorough treatment of the energy distributions of decays products at each stage will be implemented at a stage beyond this initial study.

In our Monte Carlo we use the SM $\nu N$ cross section from [13, 12] with no SUSY enhancement. In Fig. 2 of [6], they show that the $\nu N$ cross section from SM processes alone dominates by over an order of magnitude compared to any contribution to it involving the exchange of SUSY particles, for left-handed lepton mass $m_\chi \lesssim$ in the hundreds of GeV, chargino mass $m_{\tilde{\chi}} = 250$ GeV, and squark mass $m_{\tilde{q}} = 300$ GeV. This qualitative conclusion is confirmed in [19] for 50-250 GeV stau masses. To produce the largest range possible and to simplify the parameter space, we consider the case of minimal charged-current interactions ($\sin \theta_F = 0$).

We used the parametrization for the energy loss of the stau presented in [25], with

$$-\frac{dE_S}{dX} = \alpha + \beta E$$

with $\alpha = 2 \times 10^{-3}$ GeV cm$^2$ g$^{-1}$, $E_0 = 10^3$ GeV, and:

$$\beta = \beta_0 + \beta_1 \ln \left(\frac{E}{10^{10}} \text{ GeV}\right) + \beta_2 \ln \left(\frac{E_0}{10^5 \text{GeV}}\right)$$

with:

$$\beta_0 = 5 \times 10^{-9} \text{ cm}^2 \text{g}^{-1} \left(150 \text{ GeV/m}_\tau\right)$$

$$\beta_1 = 2.8 \times 10^{-10} \text{ cm}^2 \text{g}^{-1} \left(150 \text{ GeV/m}_\tau\right)$$

$$\beta_2 = 2 \times 10^{-10} \text{ cm}^2 \text{g}^{-1} \left(150 \text{ GeV/m}_\tau\right)$$

5. A mechanism that can improve the odds for steep trajectories

A heavy, charged particle will undergo energy loss along its journey through the earth due to ionization and radiative losses. A long-lived, energetic, heavy, charged particle, at production, will have a lifetime that is heavily dilated in the lab frame. However, its lifetime in the lab frame will decrease as it loses energy along its path. Therefore, for some combinations of the particle’s mass, proper
massive charged particle is of order $10^{4}$ energy $10^{4}$ (see text), as a function of stau mass and lifetime. (Left) Neutrino exceeding threshold through the signature considered in this paper observable by ANITA.

Figure 4: Probability that a neutrino at a given energy incident at approximately the chord length of a particle incident at $\sim 30^\circ$ angles (6000-7000 km for 27-35$^\circ$). However, ANITA would not be able to observe showers derived from decay products from staus that have come to rest. That is because even UHE $\nu$-N interactions ($E_{cm} = 45$ TeV for $E_{\nu} = 10^{18}$ eV, increasing as $\sqrt{E_{\nu}}$), cannot produce particles with masses that exceed the shower energies of order $10^{17}$ eV that are observable by ANITA.

We note that, as is shown in [25], the range of an UHE massive charged particle is of order $10^{4}$ km, which is approximately the chord length of a particle incident at $\sim 30^\circ$ angles (6000-7000 km for 27-35$^\circ$). However, ANITA would not be able to observe showers derived from decay products from staus that have come to rest. That is because even UHE $\nu$-N interactions ($E_{cm} = 45$ TeV for $E_{\nu} = 10^{18}$ eV, increasing as $\sqrt{E_{\nu}}$), cannot produce particles with masses that exceed the shower energies of order $10^{17}$ eV that are observable by ANITA.

Figure 5: Ratio of probabilities of a detectable tau-induced shower being produced at a 35$^\circ$ incident angle versus a 10$^\circ$ incident angle, as a function of stau mass and lifetime. (Left) Neutrino energy $10^{18.5}$ eV and (right) neutrino energy $10^{19}$ eV.

We instead consider staus that decay before coming to rest. In Fig. 3, we show the differential probability for a stau to decay along its path through the earth $dP_{\text{decay}}/dx$ as a function of the distance $x$ from its entrance point. All of these curves are produced for an initial stau energy of $10^{22}$ eV, varying the mass and proper lifetime of the particle in order to illustrate the important features.

For certain combinations of initial energy, mass and proper lifetime, if the stau decays before leaving the earth, it is most likely to decay near or at the end of its pass. This can be seen most dramatically for the grey, solid curve in Fig. 3 representing $m_{\tau} = 250$ GeV and $\tau_0 = 40$ ns. This is reminiscent of the Bragg peak, where a particle leaves most of its energy at the energy of its track due to the steep rise in $dE/dx \propto 1/\beta^2$ as $\beta$ decreases. However, in this case, the peak is in differential decay probability, and it comes about due to the particle’s decreasing Lorentz factor $\gamma$, and thus lifetime in the lab frame as it loses energy along its path. This peak at a specific distance may give a boost to the probability for ANITA to observe particles that have traversed a significant distance through the earth. We attempt to quantify this in the next section.

In Fig. 4, we show the probability for a stau produced from a neutrino that was incident at 6.5$^\circ$ (from near the horizon) to lead to a shower above threshold as a function of the stau mass and lifetime for two different energies, $10^{18.5}$ eV and $10^{19}$ eV. The strong dependence on neutrino energy is evident. One can also see that there is a diagonal region in mass-lifetime space that is most preferred for the signature to be detectable.

In Fig. 5, we plot the ratio of the probabilities that a signal is detectable if it were coming from 35$^\circ$ below horizontal compared to from 10$^\circ$. Where there is white space, there were no events from one or both angles so that a ratio could not be calculated. Recall that ratios well in excess of 1000 would be needed in order to get a preference for events at 35$^\circ$ over ones at shallow angles, and we do not find a region of parameter space that is able to overcome this factor.
6. Conclusions

We simulated the production of a stau inside the earth, from the interaction of a UHE neutrino and a nucleon to investigate the potential of ANITA as a detector for CHAMPs. Although we do not find that this signature explains an overall preference for steep events (greater than 20°), it is a mechanism that can help to skew the distribution of incident angles toward steeper angles on average.

We note that the signature of upward-going showers is quite unique among neutrino experiments in its geometry, propagating so steeply upward and moving from a more dense to less atmosphere. This could lead to showers that begin in dense atmosphere and cease to develop where the air is thinner and thus have a lengthened shower, and thus more radio emission, which is seen to some degree in experiments [14]. Further detailed modeling of the radio signal will demonstrate whether the same effect is seen in ANITA.

We recommend that ANITA seek this signature and are optimistic that it will be able to place constraints at masses that are beyond the reach of the LHC. We expect events from this signature to be more likely to come from shallow angles, while noting that a neutrino burst might be able to overcome the challenge of preferring steeper elevation angles. We think that this would be an interesting signature for other experiments searching for air showers from taus to investigate, such as BEACON, GRAND [23] and TAROGE [24].

7. Acknowledgements

We would like to thank the National Science Foundation for CAREER Award 1255557 and also the Ohio Supercomputing Center. We are grateful to Prof. John Beacom and Prof. Stephanie Wissel for helpful discussions. We also thank Brian Clark for his input.

8. References

References

[1] A. Aab et al. Improved limit to the diffuse flux of ultrahigh energy neutrinos from the Pierre Auger Observatory. Phys. Rev., D91(9):092008, 2015.

[2] G. Aad et al. Searches for heavy long-lived charged particles with the ATLAS detector in proton-proton collisions at $\sqrt{s} =$ 8 TeV. JHEP, 01:068, 2015.

[3] V. M. Abazov et al. Search for charged massive long-lived particles at $\sqrt{s} =$ 1.96 TeV. Phys. Rev., D87(5):052011, 2013.

[4] M. Ahlers. Supersymmetry on the Rocks. J. Phys. Conf. Ser., 60:171–174, 2007.

[5] M. Ahlers, J. I. Illana, M. Masip, and D. Meloni. Long-lived staus from cosmic rays. JCAP, 8:008, Aug. 2007.

[6] I. Albuquerque, G. Burdman, and Z. Chacko. Neutrino telescopes as a direct probe of supersymmetry breaking. Phys. Rev. Lett., 92:221802, 2004.

[7] I. F. M. Albuquerque, G. Burdman, and Z. Chacko. Direct detection of supersymmetric particles in neutrino telescopes. Phys. Rev. D, 75(3), Feb. 2007.

[8] L. A. Anchordoqui, V. Barger, J. G. Learned, D. Marfatia, and T. J. Weiler. Upcoming ANITA events as evidence of the CPT symmetric universe. ArXiv e-prints, Mar. 2018.

[9] S. Ando, J. F. Beacom, S. Profumo, and D. Rainwater. Probing new physics with long-lived charged particles produced by atmospheric and astrophysical neutrinos. JCAP, 0804:029, 2008.

[10] S. Chatrchyan et al. Searches for long-lived charged particles in pp collisions at $\sqrt{s} =$ 7 and 8 TeV. JHEP, 07:122, 2013.

[11] J. F. Cherry and I. Shoemaker. A Sterile Neutrino Origin for the Upward Directed Cosmic Ray Shower Detected by ANITA. ArXiv e-prints, Feb. 2018.

[12] A. Connolly, R. S. Thorne, and D. Waters. Calculation of High Energy Neutrino-Nucleon Cross Sections and Uncertainties Using the MSTW Parton Distribution Functions and Implications for Future Experiments. Phys. Rev., D83:113009, 2011.

[13] R. Gandhi, C. Quigg, M. H. Reno, and I. Sarcevic. Ultrahigh-energy neutrino interactions. Astropart. Phys., 5:81–110, 1996.

[14] C. Glaser, M. Ertlmann, J. R. Horandel, T. Huege, and J. Schulz. Simulation of radiation energy release in air showers. Journal of Cosmology and Astroparticle Physics, 2016(09):024, 2016.

[15] P. W. Gorham et al. The Antarctic Impulsive Transient Antenna Ultra-high Energy Neutrino Detector Design, Performance, and Sensitivity for 2006-2007 Balloon Flight. Astropart. Phys., 32:10–41, 2009.

[16] P. W. Gorham et al. Characteristics of Four Upward-pointing Cosmic-ray-like Events Observed with ANITA. Phys. Rev. Lett., 117(7):071101, 2016.

[17] P. W. Gorham et al. Observation of an Unusual Upward-going Cosmic-ray-like Event in the Third Flight of ANITA. 2018.

[18] S. Hoover et al. Observation of Ultrahigh-Energy Cosmic Rays with the ANITA Balloon-Borne Radio Interferometer. Physical Review Letters, 105(15):151101, Oct. 2010.

[19] Y. Huang, M. H. Reno, I. Sarcevic, and J. Uscinski. Weak interactions of supersymmetric staus at high energies. Phys. Rev., D74:115009, 2006.

[20] J. Kersten. SUSY at the Pole. Nucl. Phys. Proc. Suppl., 168:277–279, 2007.

[21] V. Khachatryan et al. Search for long-lived charged particles in proton-proton collisions at $\sqrt{s} =$ 13 TeV. Phys. Rev., D94(11):112004, 2016.

[22] M. D. Kistler and R. Laha. Multi-PeV Signals from a New Astrophysical Neutrino Flux Beyond the Glashow Resonance. ArXiv e-prints, May 2016.

[23] O. Martineau-Huynh et al. The Giant Radio Array for Neutrino Detection. EPJ Web Conf., 116:03005, 2016.

[24] J. W. Nam et al. Design and implementation of the TAROGE experiment. Int. J. Mod. Phys., D25(13):1645013, 2016.

[25] M. H. Reno, I. Sarcevic, and S. Su. Propagation of supersymmetric charged sleptons at high energies. Astropart. Phys., 24:107–115, 2005.

[26] S. Schoenen and L. Raedel. Detection of a multi-PeV neutrino-induced muon event from the Northern sky with IceCube. The Astronomer’s Telegram, 7856, July 2015.

[27] E. Zas. Neutrino detection with inclined air showers. New J. Phys., 7:130, 2005.