Snowmass2021 - Letter of Interest

The Radar Echo Telescope for Neutrinos and Cosmic Rays

NF Topical Groups:

■ (NF4) Neutrinos from natural sources
■ (NF10) Neutrino detectors
■ (CF7) Cosmic Probes of Fundamental Physics
■ (IF10) Radio Detection

Contact Information:

Steven Prohira
Department of Physics, Center for Cosmology and AstroParticle Physics, The Ohio State University, Columbus, OH 43210
[prohira.1@osu.edu]
Collaboration: The Radar Echo Telescope (RET) https://radarechotelescope.org

Authors and Abstract:

S. Prohira,[1,*] K.D. de Vries,[2,†] P. Allison,[1] J. Beatty,[1] D. Besson,[3,4] A. Connolly,[1] P. Dasgupta,[5] S. De Kockere,[2] D. Frikken,[1] C. Hast,[6] E. Huesca Santiago,[2] C.-Y. Kuo,[7] U.A. Latif,[3,2] V. Lukic,[2] T. Meures,[8] K. Mulrey,[2] J. Nam,[7] A. Novikov,[3] A. Nozdrina,[3] J.P. Ralston,[3] C. Sbrocco,[1] R. Stanley,[2] J. Torres,[1] S. Toscano,[5] D. Van den Broeck,[2] N. van Eijndhoven,[2] and S. Wissel[9]

[1]*Department of Physics, Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, Columbus OH, USA*
[2]*Vrije Universiteit Brussel, Brussel, Belgium*
[3]*University of Kansas, Lawrence, KS, USA*
[4]*National Research Nuclear University, Moscow Engineering Physics Institute, Moscow, Russia*
[5]*Université Libre de Bruxelles, Brussels, Belgium*
[6]*SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
[7]*National Taiwan University, Taipei, Taiwan*
[8]*University of Wisconsin-Madison, Madison, WI, USA*
[9]*Pennsylvania State University, State College, PA, USA*

Detection of ultra high-energy neutrinos (UHE) via radar echo detection with the Radar Echo Telescope (RET) is discussed. Radar echo detection is a highly promising technique using active radar sounding to locate short-lived ionization deposits produced by neutrino-induced particle cascades in ice. A recently published test-beam measurement at SLAC has demonstrated that radar echo detection is feasible and in accord with theoretical calculations. We present an outline of the test beam experiment, along with the theory and a brief history of the radar echo method. We describe the Radar Echo Telescope for Cosmic Rays (RET-CR), a prototype which is under development, and we discuss a dedicated full scale neutrino detector, the Radar Echo Telescope for Neutrinos (RET-N). The unique sensitivity and capabilities of the radar echo method for determining energy, direction, and flavor reconstruction of UHE neutrinos highlights the technique as one of the most promising tools of UHE neutrino physics in the future. Development of the Radar Echo Telescope over the coming decade will result in a new worldwide facility for UHE neutrino physics.

* prohira.1@osu.edu
† krijndevries@gmail.com

The promise of ultra high energy neutrinos.— Ultra high-energy (UHE) neutrinos, defined here as having energies in excess of 10 PeV, are of great interest for several reasons. They probe the sources of the highest energy particles in the universe, traveling to us directly, undisturbed over great cosmic distances. They allow us to study fundamental interactions at center-of-mass energies unreachable by terrestrial colliders. These neutrinos are produced primarily via interactions of UHE cosmic rays (charged particles accelerated to immense energies by as-yet unidentified sources) with the cosmic microwave background and extra-galactic background light. UHE cosmic rays have been detected at earth with energies several orders of magnitude higher than the highest energy neutrinos detected to date, indicating a likely flux of UHE neutrinos, with a spectrum that remains experimentally unconstrained. For more information, and exhaustive references, please refer to the UHE neutrino LOI for Snowmass 2021.

The challenge of ultra high energy neutrinos.— UHE neutrinos are, however, exceedingly rare and difficult to detect. Optical detectors such as IceCube [1], ANTARES [2] and Baikal-GVD [3], successfully measure neutrinos up to (and slightly beyond) the UHE threshold by detecting the Cherenkov light produced when a relativistic particle (or cascade of particles) moves through their detector. These detectors live in ice or water, and instrument $\sim$km^3 volumes, but even these, and future detectors [4, 5] are too small to detect a statistically significant number of UHE neutrinos, fluxes consistent with a handful of detectable neutrino events per cubic kilometer of interaction volume per decade.

A possible solution to this challenge lies in the use of radio waves, for which ice is largely transparent. Radio waves can travel an order of magnitude further than optical light in ice without attenuation, meaning that the separation between detector modules can be commensurately larger, and so too the effective detector volume. Several experiments, past, present and future [6–11] seek detection of UHE neutrinos via the Askaryan effect [12, 13], in which Cherenkov-like, coherent radio waves are produced by an UHE neutrino-induced cascade in a dense medium. Others seek to detect cascades via similar mechanisms in air, either using high-elevation arrays [14, 15], ground [16] or space-based detectors [17]. An alternative approach, described here, focuses on the ionization that these neutrino-induced cascades leave behind as they traverse a medium. Using this ionization as a reflector, cascades may be detected by remote radar echo location. [18, 19]

Radar echoes.— When a high-energy neutrino interacts in the ice, it produces a relativistic cascade of charged particles that traverse the medium. As they progress, they ionize the medium, leaving behind a cloud of stationary charge. This cloud of charge, which persists for a few to tens of nanoseconds [20], is dense enough to reflect radio waves. Therefore, to detect a neutrino, a transmitter can illuminate a volume of dense material like ice, and if a neutrino interacts within this volume, the transmitted radio will be reflected from the ionization cloud to a distant receiver, which monitors the same illuminated volume.

The primary advantages of the radar method are threefold. First, the radar system provides control over the transmitted signal, and therefore the received signal, (namely: output power level, frequency, and modulation), all of which can increase sensitivity and decrease background. Second, the radar method has excellent geometric acceptance relative to passive (Askaryan) methods, which require the detector to lie within a small angular window at the Cherenkov angle. The radar signal is detectable over a wide range of primary neutrino arrival angles for a fixed transmitter-receiver geometry, greatly increasing the sensitivity of a potential detector. These two together mean that radar may be able to continue the neutrino spectrum beyond the current optical regime. Third, because the received signal is a function of the transmitter properties and the geometry of the transmitter–cascade–receiver system, each received signal has a wealth of information that can be probed to ascertain arrival direction, primary energy, and even flavor. Current efforts to quantify these capabilities are ongoing.

Radar echoes have been proposed as a way to detect UHE particles (cosmic rays specifically) since 1940 [21]. Early experimentation demonstrated that the sporadic reflections from the atmosphere detected by early radar experiments were attributable to meteors [22], which similarly ionize trails in the atmosphere [23, 24]. Later experiments to detect UHECR in the atmosphere [25–28] were unsuccessful due to the short ionization lifetimes, collisional damping of the free ionization electrons (which limits scattering efficiency), and insufficient ionization density in air. In ice, while short lifetimes and collisional damping are present, the density of ionization is many orders of magnitude greater, since the density of ice is $\sim$1000 times that of air. This means that, while not a viable strategy for UHECR in air, detection of neutrinos in ice is feasible.

Laboratory tests.— Several attempts have been made to measure this effect in the laboratory, with some efforts successfully detecting radio reflection from continuous ionization deposits in dense material [29, 30], and others attempting to detect reflections from low-energy cascades [31]. Testbeam experiment 576 at SLAC directed an electron bunch with equivalent energy to a 10 EeV neutrino into a large plastic target, to simulate a realistic UHE neutrino induced cascade in the laboratory. This experiment observed radar reflections from particle-cascade induced ionization deposits for the first time, demonstrating the feasibility of the method [32, 33]. Further experimentation is needed to be sure that these promising laboratory results translate into nature.

The Radar Echo Telescope for Cosmic Rays.— The Radar Echo Telescope for Cosmic Rays (RET-CR, currently supported and under development) seeks to use an in-nature test beam to further test the radar echo method. When an ultra high energy cosmic ray (UHECR) interacts in the upper atmosphere, it creates a cascade, similar to that of the neutrino in ice, but at lengths of $\sim$10 km, rather than $\sim$10 m. For UHECR of sufficient energy ($\gtrsim$10 PeV), a significant fraction (10% or more) of the primary particle energy will actually reach the ice in the form of a cascade; the higher the surface elevation the greater the fraction, and at a greater range of zenith angles. This energy is contained primarily at the core of the UHECR cascade, and when it hits the ice, it produces an in-ice cascade of considerably higher energy density than the in-air cascade. This in-ice cascade will serve as the test beam for RET-CR, as a pathfinder to an eventual neutrino detector. RET-CR is under development, with planned deployment and analysis to happen within the next 4 years.

The Radar Echo Telescope for Neutrinos.— The next iteration, should RET-CR prove successful, is the Radar Echo Telescope for Neutrinos (RET-N). This is a detector that would employ the same principles as above, but directed toward detecting neutrino-induced cascades deep in the ice. Such a detector could be favorably placed in proximity to an optical detector, such as the next generation IceCube, in order to perform coincident detection. For a station consisting of a single, central 40 kW transmitter and 27 receiving antennas out radially from this transmitter, RET-N is projected to probe some flux models. For 10 such stations, the sensitivity at 10 PeV is projected to be comparable to IceCube, with the potential to complement or improve upon existing technologies at higher energies, allowing RET-N to continue detection of the neutrino spectrum beyond the optical regime. Detailed studies of the projected sensitivity are in preparation at the time of this writing.

Conclusion.— The Radar Echo Telescope is a potentially transformative technology for UHE neutrino detection, with the potential to extend the neutrino spectrum beyond the optical regime, from 10 PeV and beyond. Recent test beam measurements have demonstrated the feasibility of the method in the laboratory, with in-situ tests forthcoming. RET-CR will serve as a pathfinder experiment, and RET-N could make radio detections of UHE neutrinos within the decade.

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