Radio Detection

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10.1 IF 10: Executive Summary

Detection techniques at radio wavelengths play an important role in the future of astrophysics experiments. The radio detection of cosmic rays, neutrinos, and photons has emerged as the technology of choice at the highest energies. Cosmological surveys require the detection of radiation at mm wavelengths at thresholds down to the fundamental noise limit.

High energy astroparticle and neutrino detectors use large volumes of a naturally occurring suitable dielectric: the Earth's atmosphere and large volumes of cold ice as available in polar regions. The detection technology for radio detection of cosmic particles has matured in the past decade and is ready to move beyond prototyping or midscale applications. Instrumentation for radio detection has reached a maturity for science scale detectors. Radio detection provides competitive results in terms of the measurement of energy and direction and in particle identification when to compared to currently applied technologies for high-energy neutrinos when deployed in ice and for ultra-high-energy cosmic rays, neutrinos, and photons when deployed in the atmosphere. It has significant advantages in terms of cost per detection station and ease of deployment.

- IF10-1 While conceptual designs exist for next-generation arrays, investment in R&D can reduce cost and optimize designs.
- IF10-2 Opportunities exist in optimizing for power and simplifying: e.g. by using ASIC-based digitizer/readout (PMT) or RFSoCs (Radio Frequency System on Chip). Investigations are needed to identify synergies with experimental needs in other areas.
- IF10-3 Remote power and communications approaches of very large extended arrays can still benefit from dedicated R&D. Explore synergies with experiments in other areas, like DUNE, SKA, CTA, which also need large distance communication and synchronization.
- IF10-4 Enable future mm-wave cosmic probes through R&D and pathfinder experiments of new mmwave detectors with higher channel density relative to current CMB detectors.

10.2 Radio detection of cosmic particles

Astrophysical neutrinos, cosmic rays, and gamma rays are excellent probes of astroparticle physics and highenergy physics [6]. High-energy and ultra- high-energy cosmic particles probe fundamental physics from the TeV scale to the EeV scale and beyond.

Radio detection offers opportunities to instrument large areas on the surface of the earth. This is important because at energies above an EeV, the cross section for neutrinos interacting with matter have increased so much that the detector area becomes a more important parameter for the acceptance then the fiducial volume. At these energies, the preferred conversion targets for the neutrinos are mountains, the earth's crust, ice, or even the atmosphere. For ultra-high energy cosmic rays and photons, radio detection utilizes the air shower formed in the atmosphere.

While the optical Cherenkov technique has been enormously successful in measuring neutrinos from $\mathcal{O}(\text{MeV})$ to $\mathcal{O}(10 \text{ PeV})$, at higher energies, techniques at radio frequencies are the most promising for neutrino detection. In the energy range from 10 TeV to 30 PeV a factor of 5 in increase of sensitivity is needed in order to move from the discovery of cosmic neutrinos and the first correlation with sources to identify the sources of the cosmic neutrino flux and explore fundamental physics with high energy neutrinos.

Like in the optical, for radio techniques the two media being pursued broadly are the atmosphere and solid natural ice, the latter with emphasis on neutrinos. Both can be used to pursue science with cosmic rays, energetic neutrinos, or both. Above about 100 PeV, volumes of order 1000 km³, which can only be naturally occurring, are necessary to detect the rare astrophysical neutrino flux in this regime. Volumes of this scale are too large to instrument with the tens-of-km spacing necessary for optical sensors. This spacing of optical is set by the distance over which optical light is absorbed or scattered in the glacial ice that is used as the detection medium. However, clear ice is transparent to radio-frequency signals over distances of order 1 km, which sets the typical spacing for detectors using radio techniques.

There are many different approaches to the detection of cosmic particles at radio frequencies [4]. These approaches, the instrumentation that is unique and common to each, and future developments are described in this section.

10.2.1 Askaryan

In matter, particle cascades induced by cosmic particles produce Askaryan emission. The emission comes about from the time evolution of a charge asymmetry that develops in these particle cascades by ionization electrons moving with the cascade's front and positive ions staying behind. It is coherent for frequencies up to about 1 GHz when viewed at the Cherenkov angle and is linearly polarized perpendicular to the cascade direction and inward to its axis. Askaryan emission was measured in test beam experiments in the 2000s. It has also been observed to be emitted from cosmic ray air showers. Now, many experiments are searching for this signature from ultra-high energy neutrino interactions either from within the ice or by viewing ice from altitude.

10.2.1.1 In-ice

One approach to detecting neutrinos via the Askaryan signature is by embedding antennas into the ice itself, and the first experiment to take this approach was RICE. Since then, ARIANNA, ARA, and RNO-G [11]

search for ultra-high energy neutrinos with antennas deployed in the ice, either at shallow depths (within $\sim 10 \text{ m}$ of the surface) or somewhat deeper (up to 200 m). An integrated facility for a wide band neutrino detector is IceCube-Gen2 that will employ both optical and radio detectors. Deep detectors are employing interferometry-based trigger designs.

10.2.1.2 Balloon

Another approach to detecting the Askaryan signature from ultra-high energy neutrinos is to deploy antennas on a balloon-borne payload at stratospheric altitudes where the payload can view approximately 1.5 million km² of ice. At these altitudes, the threshold for a detection is higher, but above threshold, balloons greatly exceed ground-based approached in viewable area. The ANITA project flew four times under NASA's longduration balloon program, and the next-generation PUEO [8] is set to launch in the 2024-2025 Austral summer season with a trigger that used an interferometric approach.

10.3 Geomagnetic emission

A cosmic ray incident on the atmosphere will produce a particle cascade, and charges in the cascade produce a transverse current due to the earth's magnetic field, which produces what is known as geomagnetic emission at radio frequencies. The geomagnetic emission is coherent up to frequencies of about 1 GHz and is linearly polarized perpendicular to both the earth's magnetic field and cascade direction. The Askaryan emission mentioned above also contributes to the radio frequency signal from air showers on average at the 20-30 % level in energy density. The interplay between geomagnetic and Askaryan emission gives rise to a non-azimuthally symmetric signal pattern due to the interplay of the different radiation patterns. Both are collimated in a Cherenkov cone with an opening angle of typically a degree.

A next generation ultra-high energy cosmic particle observatory is required to exploit proton astronomy and to discover ultra-high energy neutrinos and photons. Such a next-generation cosmic particle observatory needs to cover a large area, up to $200,000 \,\mathrm{km^2}$. Radio detection is the current favorite to make deployment at this scale possible and GRAND proposed to cover an area of this size.

10.3.1 Radio detection of cosmic rays

In addition to the traditional strategies for detecting high energy cosmic rays incident on the atmosphere, which include detection of secondary particles, optical Cherenkov emission, and fluorescence emission, geomagnetic emission is a strategy that complements the others and has seen major advancements in the past two decades [9]. Radio detection of cosmic rays has a round-the-clock duty cycle and leaves a broad ($\sim 100 \text{ m}$) footprint on the ground.

10.3.2 Detection of neutrino-induced, earth-skimming air showers

The combined geomagnetic and Askaryan signatures can also be used to detect air showers that can originate from energetic tau neutrinos that are earth skimming [2]. These can produce a tau lepton through a charged

current interaction in matter, and the tau can subsequently decay to produce an electromagnetic or hadronic shower.

The detection of pulses consistent with air showers going in the upward direction has the advantage of being flavor sensitive, and has become an objective of many detectors. BEACON [10], in prototype phase, TAROGE, and TAROGE-M are compact antenna arrays in elevated locations that aim to detect UHE ν_{τ} emerging upwards via the radio emission of the air showers that they trigger. ANITA and PUEO are also sensitive to upgoing ν_{τ} , from a higher elevation. GRAND [5] is a planned experiment that will cover large areas with a sparse antenna array to detect the radio emission from air showers triggered by UHE ν_{τ} , cosmic rays, and gamma rays. This is also a neutrino signature for PUEO, the follow-up of ANITA, and many other dedicated projects instrumenting large areas with antennas such as GRAND or putting them in mountains such as BEACON and TAROGE.

10.3.3 RADAR

An alternate strategy for detection of neutrinos at radio frequencies uses RADAR [3]. 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, 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.

With this technique, a custom signal is transmitted in the ice and received after reflections from neutrinoinduced cascades. With this technique, the experimenter can determine the properties of the signal (including the amplitude, up to what is permitted to be transmitted). Also, 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. 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 with the potential to complement or improve upon existing technologies in this energy regime.

10.4 KIDs

Cosmological surveys require the detection of radiation at mm wavelengths at thresholds down to the fundamental noise limit. The detection of mm-wave radiation is important for: studying cosmic acceleration (Dark Energy) and testing for deviations from general relativity expectations through measurements of the kinetic Sunyaev-Zeldovich effect, precision cosmology (sub-arcminute scales) and probing new physics through ultra-deep measurements of small-scale CMB anisotropy, and mm-wave spectroscopy to map out the distribution of cosmological structure at the largest scales and highest redshifts.

Imaging and polarimetry surveys at sub-arcminute scales will require $O(10^6)$ detectors over a $O(10 \text{ deg}^2)$ fields-of-view (FoV) covering 9 spectral bands from 30 GHz to 420 GHz. Spectroscopic surveys (over a smaller FoV initially, $O(1 \text{ deg}^2)$, but potentially also reaching $O(10 \text{ deg}^2)$) will require a further factor of 10–100 increase in detector count. The 2019 report of the DOE Basic Research Needs Study on High Energy Physics Detector Research and Development identified the need to carry out detector R&D to achieve this goal. The driver for new technology is not the detector count but the increased detector *density*. Whereas in current experiments, the detector packing density is limited by the physical size of elements in existing demonstrated multiplexing schemes, KIDs eliminate the need for additional cold multiplexing components, allowing for arrays at the densities needed for the science aims of proposed cosmological surveys.

The kinetic inductance detector (KID) is a technology that has gained significant traction in a wide range of applications across experimental astronomy over the last decade. A KID is a pair-breaking detector based on a superconducting thin-film microwave resonator, where the relative population of paired (Cooper pairs) and un-paired (quasiparticles) charge carriers govern the total complex conductivity of the superconductor. Photons with energy greater than the Cooper pair binding energy (2 Δ) are able to create quasiparticle excitations and modify the conductivity. By lithographically patterning the film into a microwave resonator, this modification is sensed by monitoring the resonant frequency and quality factor of the resonator. Since each detector is formed from a microwave resonator with a unique resonant frequency, a large number of detectors can be readout without the need for additional cryogenic multiplexing components. In addition, the designs to be fabricated are relatively simple.

There are a number of KID-based architectures being developed for a variety of scientific applications. Direct Absorbing KIDs are the simplest variant, where the resonator geometry is optimized to act as an impedance-matched absorber to efficiently collect the incoming signal. To date, the only facility-grade KID-based instruments are based on this detector architecture, with the NIKA-2 experiment on the IRAM 30-meter telescope having demonstrated that the KID-based instruments are highly competitive with other approaches. Microstrip-coupled KIDs take advantage of recent advancements that allow for the ability to lithographically define circuits capable of on-chip signal processing with extremely low loss. The capability to robustly couple radiation from superconducting thin-film microstrip transmission lines into a KID with high optical efficiency is being developed. Thermal Kinetic Inductance Detectors take a similar approach as has been developed for bolometric transition edge sensor arrays. Instead of directly absorbed radiation breaking pairs, a thermally-mediated KID (TKID) uses the intrinsic temperature response of the superconducting film to monitor the temperature, and therefore absorbed power. It combines the multiplexing advantage of KIDs with the proven performance of bolometric designs in TES detectors, at the expense of fabrication complexity.

On-chip spectroscopy is a natural extension of multi-band imaging using on-chip filters to a filter-bank architecture to realise medium-resolution spectroscopic capability. Several approaches to on-chip spectroscopy exist at a range of technological readiness.

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