PROCEEDINGS OF SCIENCE

Towards detection of ultra high energy neutrinos at the South Pole: Askaryan Radio Array experiment latest results and future prospects

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The Askaryan Radio Array (ARA) is an in-ice ultrahigh energy (UHE, >10 PeV) neutrino experiment at the South Pole that aims to detect radio emissions from neutrino-induced particle cascades. ARA has five independent stations which together have collected nearly 30 station-years of livetime of data. Each of these stations searches for UHE neutrinos by burying in-ice clusters of antennas~200 meters deep in a roughly cubical lattice with side length ~20m. Additionally, the fifth ARA station (A5) has a beamforming trigger, referred to as the Phased Array, consisting of a trigger array of 7 tightly packed vertically-polarized antennas. In this proceeding, we review the physics results from ARA, report on the progress on the analysis of the full ARA data set, and discuss future prospects for ARA emphasizing the discovery potential and benefits for the radio community and future UHE energy detection experiments.

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1. Introduction

Ultra-high-energy (UHE) neutrinos, with energies exceeding 10^{16} eV, provide critical insights into the most energetic and distant phenomena in the universe. Due to their lack of electric charge and weak interactions, neutrinos can travel vast distances without deflection or absorption. UHE neutrinos from astrophysical sources offer a unique probe into extreme energy processes, such as those occurring in active galactic nuclei and gamma-ray bursts. Meanwhile, cosmogenic UHE neutrinos, generated through interactions between ultra-high-energy cosmic rays (UHECRs) and the cosmic microwave background, are essential for studying the origins of UHECRs.

Detecting UHE neutrinos is challenging due to their low flux and small interaction probability with matter. The most promising method is radio-based detection via the Askaryan effect, where neutrino interactions in dense media like ice produce coherent Cherenkov radiation in the radio frequency range. In Antarctic ice, radio waves can travel distances of 1 km or more, allowing large volumes to be monitored for neutrino interactions.

The Askaryan Radio Array (ARA) at the South Pole utilizes this technique, with an array of radio antennas buried deep in the ice to detect radio signals from neutrino interactions. As one of the most advanced radio-based neutrino observatories, ARA has been collecting data for over a decade and holds the largest dataset among similar experiments. This paper summarizes ARA's current status, ongoing data analyses, and future upgrades.

2. A historical perspective

The history of radio-based neutrino detection began with Soviet-Armenian physicist Gurgen Askaryan in the 1960s, who proposed the mechanism of coherent radio emission from particle cascades in dense media [1]. This laid the groundwork for in-ice radio neutrino detectors. The first experiment to implement this concept was the Radio Ice Cherenkov Experiment (RICE) [2], which deployed antennas at the South Pole in 1996. RICE demonstrated the feasibility of radio techniques for neutrino detection and set early limits on ultra-high-energy (UHE) neutrino flux.

Three second-generation experiments followed: ANITA, a balloon-borne detector that circled Antarctica, listening for neutrino-induced radio emissions; ARIANNA, which used shallow Log-Periodic Dipole Arrays at Moore's Bay; and ARA, which deployed deep antenna arrays at the South Pole. These experiments improved upon RICE's UHE neutrino limits. The latest experiments, such as RNO-G in Greenland, combine ARA-like deep antennas with ARIANNA-style shallow arrays, and PUEO, ANITA's successor, are designed to have higher sensitivity to neutrino signals. IceCube-Gen2, with both optical and radio detectors, aims to significantly increase UHE the volume instrumented for neutrino detection. This paper focuses on the ARA experiment, which has operated for 10+ years and holds the largest dataset among similar experiments.

3. ARA detector overview

The current ARA configuration consists of five stations arranged in a 2-km triangular grid, as shown in Figure 1. The figure also indicates the South Pole Station, the plane landing strip, and the IceCube experiment perimeter. ARA stations are connected to the IceCube Laboratory via cables for power and data transmission.

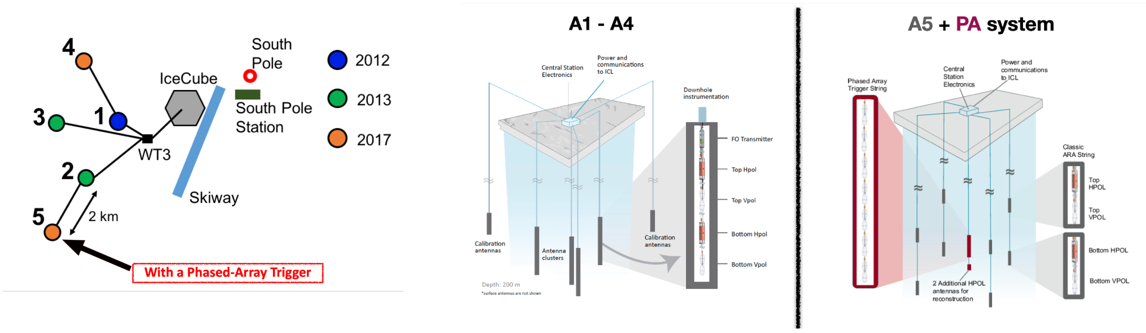

Figure 1: (Left) Grid arrangement of the stations A1-A5. (Right) A schematic view of individual stations.

A standard ARA station (Figure 1) is equipped with 16 radio antennas: eight vertically polarized (Vpol) birdcage dipoles and eight horizontally polarized (Hpol) quad-slot cylinder antennas. These antennas are arranged in a cuboid structure at depths of roughly 170 and 190 meters, with pairs forming a square grid with a side length of about 20 meters.

The latest station, A5, includes a phased array system, consisting of an additional string of seven closely spaced Vpols and two Hpols. This setup allows an impulsive signal's wavefront to hit each antenna in succession at equidistant time intervals. Signals from the individual antennas are combined using time shifts to form a coherent sum. This method suppresses noise and enhances signal detection, improving sensitivity to faint signals. The phased array is integrated into the station's trigger, boosting detection capability.

ARA was the first experiment to deploy a phased array system for neutrino detection and has published a neutrino search paper based on its data [4]. This advancement has been adopted by newer experiments such as RNO-G, PUEO, and the forthcoming IceCube-Gen2, demonstrating its effectiveness in enhancing detection capabilities.

4. Diffuse neutrino flux searches

One of the most significant recent publications utilizing data from the stations A2 and A3 collected over a span of four years was released in 2020 [3]. In 2022, ARA published a new paper detailing the first neutrino search conducted using the phased array system at station A5 [4]. This analysis was based on a smaller dataset, covering only 7 months of data, yet it marked the first neutrino search utilizing the phased array technology and demonstrated improved analysis efficiency compared to that with traditional ARA stations.

ARA is currently analyzing the full ARA dataset, which includes 23.9 station-years of livetime from the traditional ARA stations and 3.8 station-years from the phased array at station A5. This dataset is more than three times larger than in previous analyses. Two key papers are planned: one reporting on the full 5-station analysis, offering the best limit on neutrino detection to date, and another focusing on a "hybrid" analysis combining data from phased array and standard antennas of station A5, showcasing the strength of such combined approaches. This method serves as a model for future analyses in experiments like RNO-G and PUEO.

The analyses are in its final stages, with calibrations being complete and event selection nearing finalization, though the data remains blinded. The current status has been shared in more detail at

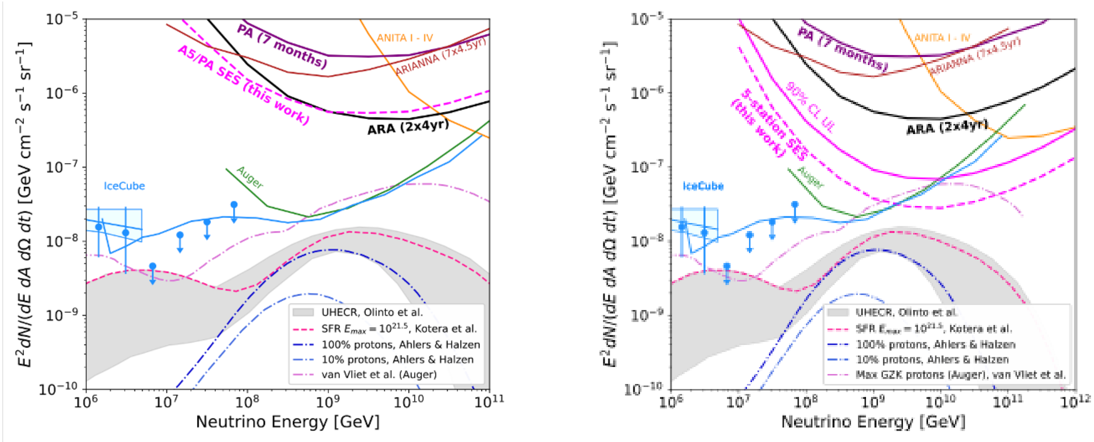

Figure 2: Projected sensitivity of the ongoing ARA analysis for the A5/PA search (left) and the five-station full-dataset analysis (right).

recent conferences [5]. With this large dataset, ARA holds the greatest potential for discovering neutrinos and can probe energies up to EeV scales. Figure 2 shows the projected diffuse flux limits, which are expected to surpass those of the Auger and IceCube experiments.

5. Ice properties

The 2.8-km thick ice sheet at the South Pole is the dense medium used by the ARA experiment, and understanding its properties is crucial for detecting and reconstructing neutrino interactions. However, the propagation of radio-frequency electromagnetic waves over distances of 1 km or more in ice is not fully understood. Key properties include the index of refraction with depth, frequency-dependent attenuation length, and ice birefringence. Reflective layers within the ice can further impact signal detection. The situation is complicated by varying ice density with depth and ice flow, which aligns ice grains. Additionally, electromagnetic waves in the ice curve rather than travel in straight lines, creating "shadow zones" where signals cannot reach detectors.

ARA has conducted extensive ice calibration studies using radio transmitters that send pulses to the stations. Each station has in-situ calibration pulsers, with additional signals from two deep transmitters deployed with IceCube strings and surface pulsers. A significant calibration effort involved data collection from a transmitter lowered into a borehole by the SPICECore experiment. These efforts have greatly advanced our understanding of the RF properties of the ice medium, with results published in numerous journal articles over the last six years [6–12].

6. Data Acquisition Upgrade: ARA-Next

A recent development in ARA is the planned DAQ upgrade. The current DAQ is based on a custom motherboard with a straightforward trigger logic implemented in an FPGA. In this system, an event is captured whenever three out of the eight Vpol or Hpol antennas detect a pulse above a preset threshold. However, the system's sensitivity to neutrino signals is constrained by thermal noise, anthropogenic noise, and other background sources.

The new DAQ system under development will be based on Radio Frequency System-on-Chip (RFSoC) technology. In RFSoCs, the front-end ADCs are tightly integrated with data processing in a single system, offering a more efficient and power-saving architecture. This new system allows for the implementation of more sensitive and complex triggering mechanisms, including the possibility of machine learning-based triggers using neural networks. These advanced triggers have the potential to enhance the detection of faint neutrino signals in a noisy environment.

Prototypes of the new DAQ system are planned for deployment in the polar season after next, with a full upgrade of all stations scheduled for the following season. This upgrade is expected to significantly improve the sensitivity and performance of the ARA experiment, opening increased possibilities for neutrino detection.

7. Conclusions

The ARA experiment continues its successful operation at the South Pole, focused on the detection of ultra-high-energy neutrinos originating from beyond our solar system. ARA currently possesses the largest dataset among analogous experiments, and two significant papers presenting physics results are expected to be published within the next year. In addition to advancing the field of astroparticle physics, ARA's studies are contributing valuable insights into glaciology. Furthermore, ARA is contributing to the design of the future ultimate neutrino telescope IceCube-Gen2 Radio.

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