Radar points the way to detecting cosmic neutrinos

A laboratory experiment at SLAC offers the first observations of radio-wave reflections from ionization trails of particle showers in a transparent solid.

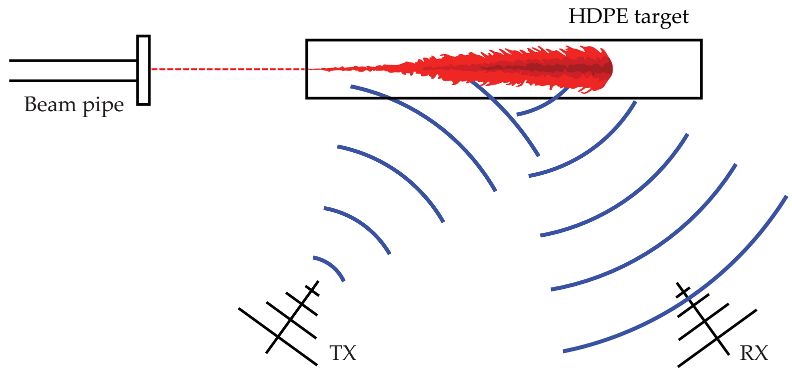

FIGURE 1. RADAR ECHOES IN ARTIFICIAL ICE. Electron bunches shot into high-density polyethylene (HDPE) create a cascade of relativistic particles that mimic those produced in ice by cosmic neutrinos. At the same time, radio waves from a nearby transmitter (TX) reflect from an ionized trail in the cascade's wake and are detected by an antenna (RX). (Adapted from ref. 1.)

Cosmic rays—the electrons, protons, antiparticles, and nuclei that penetrate Earth's atmosphere—can exceed 10^{20} eV. Accelerating particles to such high energies requires a violent, impulsive process, such as the merger of neutron stars, the collapse of a massive star, or the rapid conversion of a supermassive black hole's rotational energy. Ultrahigh-energy neutrinos are thought to emerge from such exotic sources (see the article by Peter Mészáros, PHYSICS TODAY, October 2018, page 36). But unlike cosmic rays, which interact with photons from the cosmic microwave background and are deflected by magnetic fields, cosmic neutrinos point directly back to their sources—the most powerful accelerators in the sky.

The neutrinos' feeble interaction with matter makes them powerful messengers of new physics, but it also complicates their detection. For example, the IceCube neutrino observatory in Antarctica relies on catching the flashes of Cherenkov light from muons produced by neutrinos inside a billion tons of ice. The 1 km^3 observatory requires an array of more than 5000 photomultiplier tubes because the flux of ultrahigh-energy neutrinos is so small and plummets with neutrino energy. The highest-energy neutrinos IceCube ever measured are a few peta-electron volts (1 PeV = 10^{15} eV).

How energetic is such a neutrino? One joule is about 10^{19} eV, roughly equivalent to the energy of a slow-pitched baseball. At one-thousandth of a joule, 10 PeV is the kinetic energy equivalent of a honeybee in flight. But whereas the honeybee's energy is distributed over some 10^{23} atoms, extreme astrophysical events concentrate the energy in a single cosmic neutrino. To have much chance of catching one, you need to increase the search volume or change methods.

An international collaboration led by Steven Prohira (a postdoctoral fellow at the Ohio State University) now reports[1] a proof-of-concept measurement of an old proposal: using radar to detect the interaction of a neutrino in ice. The approach requires no new technology and could scan potentially enormous volumes inexpensively. More importantly, it could detect neutrinos in an energy window that is a blind spot to existing methods.

Radio waves

In 1962 Gurgen Askaryan realized that air showers, or cascades, of relativistic electrons, muons, and other particles that beget Cherenkov light contain a negative-charge excess of about 10–20%.[2] The charge asymmetry generates coherent radio waves, whose power scales with the square of the primary particle's energy. With that scaling, the RF signal should be most intense at ultrahigh energies. The ANITA collaboration's experiment—made of an array of radio antennas hanging from a helium balloon (see PHYSICS TODAY, December 2010, page 22)—repeatedly monitors a million square kilometers of Antarctic ice during month-long flights in search of Askaryan's predicted radio waves from neutrino-triggered cascades. Other radio projects look for signals from Greenland's ice pack and from the lunar regolith. (See the article by Francis Halzen and Spencer Klein, PHYSICS TODAY, May 2008, page 29.)

Twenty years before Askaryan's work, Patrick Blackett and Bernard Lovell considered another signature of cascades—although at the time the two researchers had cosmic-ray-induced cascades in mind, not neutrino-induced ones. As a cascade travels through the atmosphere, it ionizes oxygen and nitrogen atoms and leaves a plasma trail of quasi-stationary electrons. Blackett and Lovell calculated that the ionization trail should be observable when radio waves are bounced off it.[3] But despite decades of attempts, no one has ever been able to capture either a cosmic-ray- or neutrino-triggered event that way.

As Krijn de Vries (Vrije University Brussels) and coworkers realized just a few years ago,[4] the ionization trail in air is too dilute to robustly reflect a signal. But they calculated that a cascade through ice, whose density exceeds that of air by a factor of 1000, produces a far denser plasma trail of electrons in its

FIGURE 2. THE EXPERIMENT AT SLAC. Electrons exit the beam pipe (far left) and enter the 4-m-long polyethylene target, surrounded by transmitter and receiver antennas (circled). Second from left is the transmitter; the others are receivers. (Adapted from ref. 5.)

wake, about 10 m long and 10 cm wide. Prohira, de Vries, and their colleagues now report[1] the first convincing measurements of radar reflections from the ionization trail of high-energy particles in a transparent solid.

Electrons stand in for neutrinos

Prohira and his coworkers were not looking for neutrino interactions. Their experiment at SLAC was designed to mimic a neutrino-triggered cascade by using electrons as a proxy for neutrinos and high-density polyethylene (HDPE) as a proxy for ice. Figure 1 depicts the basic concept: Intense bursts of a billion electrons are repeatedly shot into the HDPE, each time producing a cascade (red) equivalent to what's expected from a 10^{19} eV neutrino interaction in ice. Radio waves are transmitted into the polymer at the same time, and antennas around it detect any echoes reflected from free electrons in the cascade's wake.

Ice is nearly transparent to radio waves. Whereas Cherenkov light travels only about just 200 m in ice, radio waves travel an order of magnitude farther. Transmitting and receiving antennas may thus be spaced much farther apart than IceCube's photomultiplier tubes.

Unlike IceCube, ANITA, and other passive-monitoring experiments, radar is an active system. Says de Vries, "Radar provides tremendous control over all our experimental parameters. The signals we receive largely depend on what we send." The transmission power is one adjustable knob: The higher the power, the brighter the reflection. And above a critical primary-particle energy of about 10 PeV, the cloud of free electrons produced in its wake is dense enough to reflect a 0.1–1 GHz radar signal coherently. All the free reflecting electrons radiate in phase.

Transmission frequency also matters for another reason. The ionization trail in ice lives just a few nanoseconds before the free electrons reattach to nearby water molecules. To capture an electron's oscillation before it dies, the transmission frequency must be on the gigahertz scale.

Perhaps radar echo's most advantageous feature is its peak energy sensitivity, which is in the 10- to 100-PeV window, a blind spot for other neutrino-detection methods. Those energies are above what IceCube can efficiently resolve given its low volume, and they are below the limits of balloon-borne, satellite-borne, and some in-ice experiments.

Improving signal to noise

In the new experiment, radio noise turned out to be two orders of magnitude higher in amplitude than the expected signal. The noise was largely from "transition radiation," produced when a charged particle crosses the interface between materials having different indices of refraction—in this case, from the vacuum of the beam chamber into the air of the lab or into the polyethylene slab. Transition radiation won't be a problem when researchers eventually

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look for ionization trails from neutrino-induced cascades. In nature, those cascades take place inside the ice. But in the proof-of-concept experiment, the researchers had to address the transition radiation. Fortunately, that RF noise was similar from pulse to pulse.

To extract persuasive evidence of a cascade reflection, the researchers filtered out of their data the transition radiation and other noise—Askaryan RF fields, telecommunication signals, and reflections from concrete and metal features in the SLAC station, shown in figure 2. They performed three types of experiments: ones with both the electron beam and radar on; ones with the radar on but not the electron beam; and ones with the electron beam on but not the radar. Armed with those data, they subtracted the background to resolve a real radar signal. To constrain the analysis, they confirmed that the signal had the expected timing, frequency, and power dependence.

Prohira and his colleagues next want to repeat the experiment on a high-altitude ice sheet in Antarctica. It's radio quiet there—though even the passage of wind generates residual RF hum—and the altitude increases the likelihood that a cosmic-ray-induced cascade will make it into the ice; the ionization trail will come from that cascade. Antennas just below the surface would transmit radar and pick up reflected signals.

After that in-nature test the researchers will turn their attention to neutrino-induced cascades.

Mark Wilson

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Localized electric field manipulates a nuclear spin

The atom-level control could provide the precision required for some quantum computing applications.

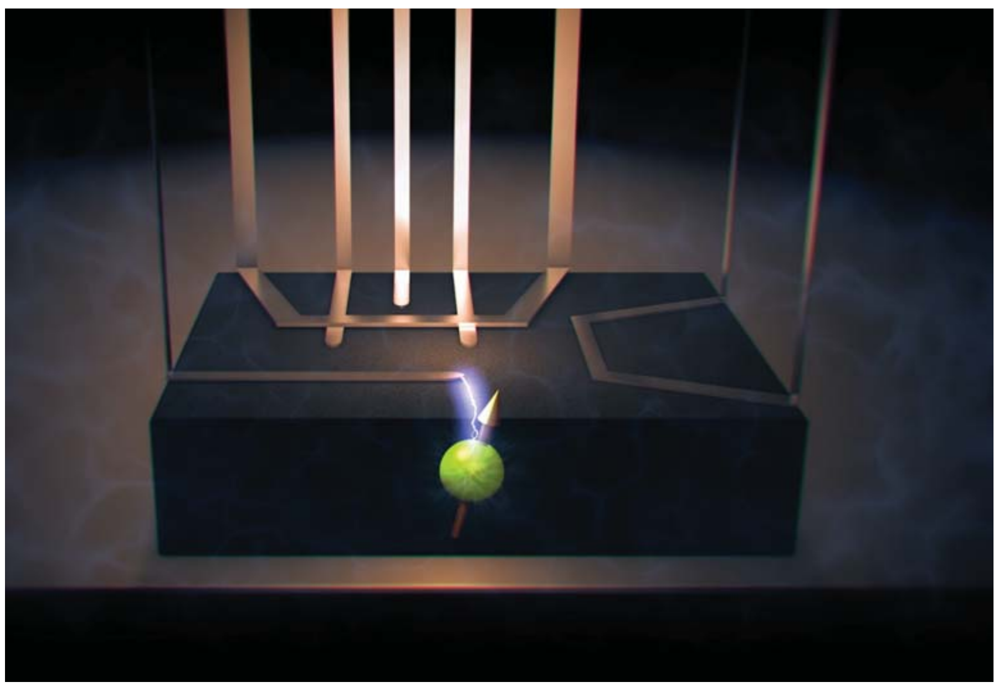

FIGURE 1. IN THIS ARTIST'S IMPRESSION of a nuclear electric resonance device, a sharp metallic antenna applies a strong oscillating electric field directly to an antimony atom (green) embedded in a silicon chip. Other metallic components include electrostatic gate connections and readout electrodes. (Image by Tony Melov/UNSW.)

One promising approach for quantum information processing involves embedding tightly spaced arrays of identical atomic nuclei in a silicon substrate. In that design, each nucleus's spin serves as a quantum bit, or qubit. The qubit's spin, which can be set to different states, is used to store and process information. However, before spin-based devices can be scaled up for practical use, quantum engineers need to be able to control a single nuclear spin in silicon without affecting adjacent spins.

In principle, NMR could do the job. Radio-frequency (RF) magnetic field pulses can excite and control nuclear spins that are polarized in a static magnetic field. Because of the pulses' wide spatial extent, however, they tend to influence adjacent spins, which renders NMR impractical for manipulating individual spins in a collection of identical atoms. Ideally, a method for controlling individual nuclear spins would match the ease of exciting individual electron spins in a row of semiconductor quantum dots, in which each dot is equipped with a separate electrode. Adapting that approach for nuclear spins offers a potential advantage because nuclear spins have longer coherence times than electron spins and can be measured with minimal readout error.

Electric fields, rather than magnetic ones, provide an intriguing possibility for nuclear spin control. The fields can be efficiently routed and tightly confined in complex nanoscale devices. Indeed, highly focused electric fields make possible the sophisticated interconnections found in modern silicon computer chips.

Now researchers in Andrea Morello's lab at the University of New South Wales in Australia have demonstrated electrical control over nuclear spin.[1] The re-