Compound interest

Rare exceptions aside, most scientific knowledge comes from many individuals making small advances that, ultimately, come together to produce something more profound. Biologists, for example, would not possess the revolutionary new CRISPR gene-editing technology were it not for painstaking research exploring bacterial defence mechanisms against viral infections. We see similar brick-by-brick advances every day — a slightly faster simulation algorithm, or a more reliable method for synthesizing some chemical compound.

Or consider a recent proof-of-principle demonstration (see Prohira, S. et al. *Phys. Rev. Lett.* **124**, 091101; 2020) of a radar-based technique to detect high-energy neutrinos. It's not a profound breakthrough, just a small but significant contribution to the ongoing effort, now more than 50 years old, to discover the origin of ultra-high-energy cosmic rays. Typically protons or larger nuclei, these particles have energies of 10^{19} eV or more and originate, as far as we know, more than 10^{13} km away in the most distant parts of the Universe. They might come from supermassive black holes, or supernovae, or some other exotic object. So far, no single cosmic ray source has been identified.

The biggest obstacle to understanding is what happens to cosmic rays on their way to Earth. Magnetic fields in intergalactic space or inside the Milky Way deflect charged cosmic rays, so their direction of arrival at Earth doesn't reflect their initial origin. These particles also interact with the cosmic microwave background, which further influences their motion.

Hence, the desire to detect neutrinos, which aren't bent by magnetic fields or perturbed by the microwave background. In principle, some of these neutrinos arriving at Earth may have been created in the same events as the cosmic rays themselves, so their paths may point back to those particles' places of origin. Many other neutrinos get created when cosmic rays interact with the microwave background. These 'cosmogenic neutrinos' carry information about the number of cosmic ray sources, as well as their distances.

So detecting neutrinos is of first-class interest to cosmic ray researchers. But doing so depends on the time-consuming and somewhat unglamorous work of building better neutrino detectors. At the moment, no one kind of detector is enough, as it requires multiple designs to cover neutrinos of different energies. Ongoing development in this field illustrates the tedious and ordinary scientific work required to set the stage for future headline discoveries.

One basic strategy for neutrino detection is to look for the radiation created when a high-energy neutrino interacts with matter, producing a relativistic cascade of further particles. This also generates a trail of non-relativistic electrons and nuclei as the relativistic particles lose energy in the medium. For a neutrino interacting inside ice, for example, the full time-integrated cascade profile is an ellipsoid of length about 10 m and radius 0.1 m.

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These events can be detected from Cherenkov radiation streaming away from fast electrons and positrons as they travel through the medium. This is the aim of the IceCube Neutrino Observatory located beneath the ice in Antarctica. IceCube detectors are sensitive to neutrinos with energies in the range TeV–PeV, or 10^{12} to 10^{15} eV, or very slightly above.

Another approach to neutrino detection is to look for the decay products of high-energy leptons created by neutrinos passing through Earth. A decaying lepton produces a cascade in the air, and an electric current moving relativistically through the Earth's geomagnetic field. This leads to coherent radio emission. A series of experiments (see Álvarez-Muñiz, J. et al. *Sci. China Phys. Mech. Astron.* **63**, 219501; 2020) aims to detect this radiation, or to detect the fluorescence or Cherenkov light from such in-air decays with balloon-or satellite-borne experiments. These methods have potential for discovery at very high energies — above 10^{17} eV — but limited sensitivity at lower energies.

But these detectors and other existing detectors still leave a neutrino blind spot in the energy range 10–100 PeV. Covering this gap is the aim of the recent research on radar-based neutrino detection. Here the idea is to simply use reflected radio waves to detect any particle cascade and resulting ionization cloud an interacting neutrino creates in a solid. As of now, this is the only technique expected to have peak sensitivity in the 10–100 PeV range. Hence, the first actual demonstration brings the hope of full coverage of the high-energy neutrino spectrum one step closer to reality.

In the recent proof-of-principle demonstration, the researchers didn't actually rely on neutrinos, but instead used a pulse of electrons to trigger a cascade within their target. This greatly reduced the time required for the experiment, which used an electron beam at the SLAC National Accelerator Lab in California. The researchers directed intense bursts of well-focused, high-energy electrons into a target made of high-density polyethylene, and chose electron energies so that any resulting cascade would have a particle density much like that expected for a typical high-energy neutrinos impinging on Earth.

To see any triggered particle cascade, the researchers sent a continuous beam of radio waves toward the target in a direction perpendicular to the electron beam, and set up a receiving antenna to detect any reflection. One technical obstacle: the mere passage of the dense electron beam through the target would create radio waves 10 to 100 times stronger than any reflection from a cascade event. Hence, identifying the smaller cascade signal within this larger background required careful data analysis. In a series of preliminary experiments, the researchers measured the radio waves created merely by the electron beam — even in the absence of any cascade events — and found them to be consistent from one pulse to the next. They could then subtract this background radiation from that full signal measured when observing the electrons moving through the target. Any remaining signal came from cascades.

This laboratory demonstration will need to be replicated in nature, perhaps deep beneath the ice of the Antarctic, a region penetrated only by neutrinos. If it works as expected, physicists will expand in an important way their set of tools for searching for the origins of cosmic rays. We don't know the source of matter of these particles, nor where they get their energy. But we're one small step closer to finding out. Many small steps often take us to remarkable places. ❐

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