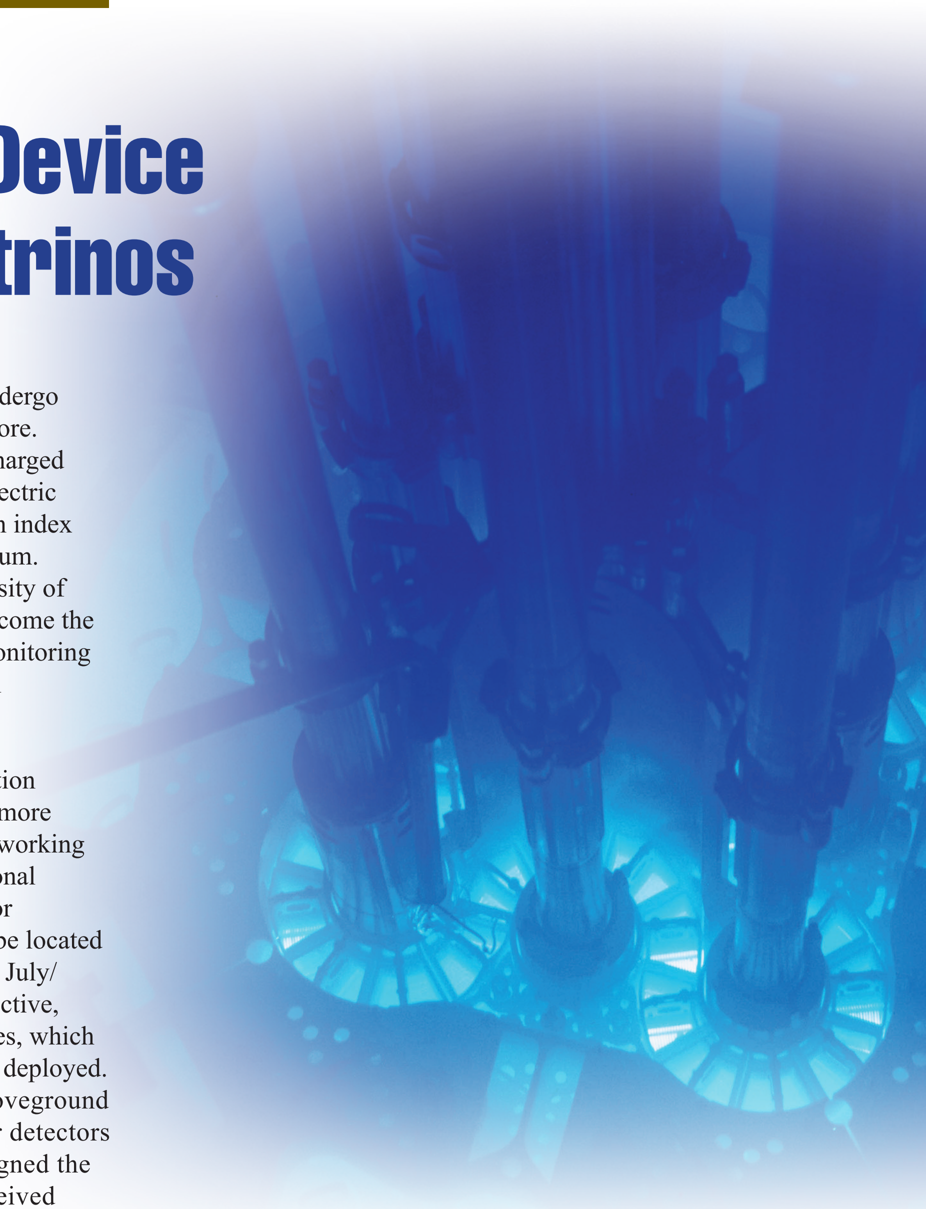
A Discriminating Device to Detect Antineutrinos



Inside a nuclear reactor such as the Advanced Test Reactor at Idaho National Laboratory, Cerenkov radiation (the blue glow) is produced as part of the fission processes occurring within the reactor core. This same radiation could be useful in detecting antineutrinos. (Courtesy of Idaho National Laboratory.)

INSIDE a nuclear reactor, as uranium and plutonium undergo fission, an eerie, blue glow emanates from the reactor core. Called Cerenkov radiation, this light is produced when charged particles travel faster than the speed of light within a dielectric (nonconductive) material, such as water, whose refraction index reduces the light's speed from what it would be in a vacuum. Cerenkov radiation is typically used to measure the intensity of the fission processes within a reactor. Now, it has also become the basis for an antineutrino detector designed to improve monitoring capabilities at nuclear facilities and enhance international nonproliferation efforts.

With funding from the National Nuclear Security Administration's Office of Nonproliferation and Verification Research and Development, scientists at Lawrence Livermore and Sandia national laboratories in California have been working together for years to build antineutrino detectors for national security applications. Previous prototypes used scintillator materials to detect these elementary particles and had to be located underground in an area near a reactor's core. (See *S&TR*, July/August 2008, pp. 23–25.) Although the devices were effective, not all reactors have underground galleries near their cores, which limits the number of sites where those detectors could be deployed.

A new water-based detector designed to operate aboveground would be easier to install than underground scintillator detectors and would reduce the environmental impact. "We designed the water-based detector based in part on feedback we received from IAEA [the International Atomic Energy Agency]," says Livermore physicist Adam Bernstein, who leads the project team. "IAEA wanted a device that could be shipped to a reactor site and easily positioned for monitoring. Our sponsors agreed that this would be a useful advance in the technology."

IAEA is the world's watchdog for monitoring nuclear reactors to ensure that nuclear materials in the reactor core are not diverted for use in weapons. By detecting antineutrinos—a natural by-product of the fission of uranium-235 and plutonium-239 within a reactor core—authorities can accurately monitor a reactor's thermal power and fissile inventory and determine if further facility inspections are needed. (See *S&TR*, January/February 2006, pp. 21–23.) An aboveground antineutrino detector could be more efficient than the underground technology for determining whether nefarious activities are afoot.

The Antineutrino Two-Step

Detecting antineutrinos is a tricky business, partly because of their elusive nature. These nearly massless, uncharged particles have a low interaction probability. That is, they can travel hundreds of thousands of kilometers without ever interacting with matter. Researchers can compensate for the low interaction probability by taking advantage of the huge flux of antineutrinos that pass through detectors located a few tens of meters from a reactor's core. Tests using prototype devices reliably measured a few hundred interactions per day—an event rate high enough to accurately predict whether a reactor is operating under normal conditions.

The antineutrino signal produced within a scintillator detector consists of two bright flashes of light that occur almost simultaneously, just a few tens of microseconds apart. Initial prototype detectors used scintillator doped with gadolinium to enhance this two-step signal. When an antineutrino collides with one of the many protons available within the scintillator–gadolinium mixture, it produces a positron and a neutron. The positron soaks up most of the antineutrino's energy and creates a flash of light as it travels through the medium, before rapidly annihilating on an electron. The neutron loses energy as it bounces off protons in the scintillator, until it is absorbed by a gadolinium nucleus about 30 microseconds after the positron flash.

The captured neutron puts the nucleus into an excited quantum state, from which it immediately decays, giving off gamma rays. The gamma rays transfer energy to electrons, which then scintillate as they move through the medium, creating the second flash of light. Photomultiplier tubes detect the light from both flashes, and computer software analyzes and stores the information.

Detectors with a vat of homogenous scintillation fluid require a substantial amount of shielding, such as lead or polyethylene, as well as rock overburden to protect the material from background radiation in the environment, such as high-energy neutron radiation induced by cosmic muons. These particles rain down on the detector and mimic the antineutrino signal. “One challenge to building an aboveground detector was figuring out how to reduce the cosmic-ray-induced neutron background,” says Bernstein. “By using water instead of scintillator fluid, we've built a detector that may be able to do just that.”

A Need for Speed

The water-based detector creates antineutrino signals in much the same way that scintillator detectors do. However, instead of creating scintillation light, the positron and neutron produce weaker but still detectable flashes of Cerenkov light. The first blue flash is created by the positron as it moves faster than the speed of light through the water–gadolinium mixture. A gadolinium nucleus captures the neutron, creating a cascade of gamma rays, which then generate fast Compton-scattered electrons that produce the second flash of Cerenkov light.

“We first considered doping water with gadolinium about 10 years ago to build detectors for identifying antineutrino bursts from nuclear explosions,” says Bernstein. “We had to shelve the concept because at the time the detectors would have been too big to deploy. The nonproliferation community became interested in the technology when more recent tests showed that small aboveground devices could reject background radiation, so we began to work on the idea again.”

Water has a potential advantage over scintillator fluid for an aboveground detector because water makes the detector impervious to background radiation produced from high-energy neutrons. These cosmic particles are common at the surface of Earth and are the main source of background in scintillator detectors. When high-energy neutrons collide with protons in a scintillation mixture, the protons recoil, generating scintillation pulses. This interaction slows down the neutron, causing it to undergo neutron capture and produce another pulse of light. The two bright pulses occurring close in time are detected by the photomultiplier tubes and are recorded as if they were an antineutrino's signal.

Livermore postdoctoral researcher Greg Keefer (left) carefully cleans the interior surfaces of a shell for a prototype antineutrino detector prior to installing other components. Dust or dirt could cloud the water and decrease the antineutrino signal strength. Laboratory physicist Steve Dazeley (right) assembles a photomultiplier tube array at the top of the prototype. Without shielding, the entire detector measures about 1 cubic meter.

The antineutrino detector fits inside a standard cargo container (right) along with the electronics needed to record, analyze, and store data. The detector was built at Livermore and assembled in its shield at Sandia National Laboratories, California, before being transported in the container to the San Onofre Nuclear Generating Station (background) for testing.

In water, the high-energy neutron hits the proton, and the proton recoils. However, the proton does not have enough speed to reach above the threshold for producing Cerenkov light. "A proton is about 2,000 times heavier than an electron, which makes it difficult to budge," says Bernstein. "Most neutrons near Earth's surface just don't have the energy to induce proton recoil velocities greater than the speed of light, so the Cerenkov flash is never generated." As a result, only one flash is produced when the captured neutron creates the familiar gamma-ray cascade, so the event is rejected. Because the water-based detector effectively eliminates the signal from high-energy neutrons, it requires far less overburden shielding and thus should function well aboveground.

A Perfect Match

The antineutrino detector effort builds on the Livermore–Sandia team's pioneering studies of antineutrino-based monitoring applications as well as research into dark matter and other basic nuclear and atomic science, including neutrino oscillations. (See *S&TR*, April 2003, pp. 13–19.) Bernstein adds that the team's work reflects a natural synergy between fundamental experimental science and the multifaceted nonproliferation programs at the national laboratories. In addition to Bernstein, the team includes Nathaniel Bowden, Steve Dazeley, and Greg Keefer at Livermore and Dave Reyna, Scot Kiff, Jim Brennan, Jim Lund, and Belkis Cabrera-Palmer at Sandia/California.

The Livermore–Sandia team recently deployed a prototype aboveground detector at the San Onofre Nuclear Generating Station in southern California, where the underground prototypes were installed. For the next several months, the detector will undergo testing to determine its accuracy and overall effectiveness. "We'll need three to six months to demonstrate that we have a stable, antineutrinolike signal," says Bernstein. "Ironically, the best evidence for the existence of that signal is when the reactor is shut down, which should reduce the antineutrinolike event rate. If the signal drops by a statistically significant amount, we can have high confidence that we are actually registering reactor antineutrinos."

The next reactor shutdown at San Onofre is scheduled for the end of 2010. Team members will operate the prototype through the shutdown and check for the change in the measured antineutrino rate. In addition, they will use other analysis methods and data checks to ensure that they are tracking antineutrinos rather than reactor-generated gamma rays or neutrons. "This test would represent a first-ever demonstration of the concept," says Bernstein. "We'll need to perform additional testing and extensive evaluations before a working detector can be deployed by an agency such as IAEA." Ultimately, the automated device could make monitoring nuclear reactors easier, less time consuming for personnel, and more cost effective.

And other detectors are in the works. "New designs will focus on reducing a detector's footprint from the size of a standard office to that of a small table," he says. The team is also working with industrial partners to develop water-based neutron detectors for other national security applications. By furthering their understanding of the smallest building blocks of the universe, scientists are improving the nation's security one antineutrino at a time.

—Caryn Meissner

Key Words: aboveground antineutrino detector, Cerenkov light, International Atomic Energy Agency (IAEA), nonproliferation, nuclear reactor, San Onofre Nuclear Generating Station, scintillator.

For further information contact Adam Bernstein (925) 422-5918 (bernstein3@llnl.gov).