The Curious History of Neutrinos and Nuclear Reactors

By Jonathan Link, Patrick Huber, and Alireza Haghighat

Neutrinos steal energy from the core and seemingly offer little in return. The science and history of neutrinos are closely linked to those of nuclear power, but if science and history are any guide, this ne'er-do-well particle may yet contribute to our nuclear future.

On June 14, 1956, Frederick Reines and Clyde Cowan called Western Union to dictate a telegram. They were flush with the "glorious feeling" that often comes with important scientific discoveries. A feeling of knowing that only you, and perhaps a few of your closest collaborators, know something that nobody else in the world knows, and a feeling of pride for your part in a momentous discovery.

Professor W. Pauli

We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters.

Frederick Reines, Clyde Cowan

Twenty-six years earlier, the exciting new field of nuclear physics was facing a serious crisis. Nuclear beta decay, in which a nucleus emits an energetic electron and moves one spot up on the periodic table, appeared to violate energy conservation, a central tenant of physics then and now. At that time, it was believed that beta decay involved only two particles in the final state: the daughter nucleus and the beta particle (or electron). The rules of energy conservation say that when a given nucleus decays into two final state particles, each should have the same energy every time. Instead, the beta particle was observed to have a broad spectrum of energies. The evidence was so compelling that Niels Bohr, who was seen by his peers as the godfather of quantum mechanics, began to argue that energy conservation might not apply in the nuclear realm, at least not on a case-by-case basis.

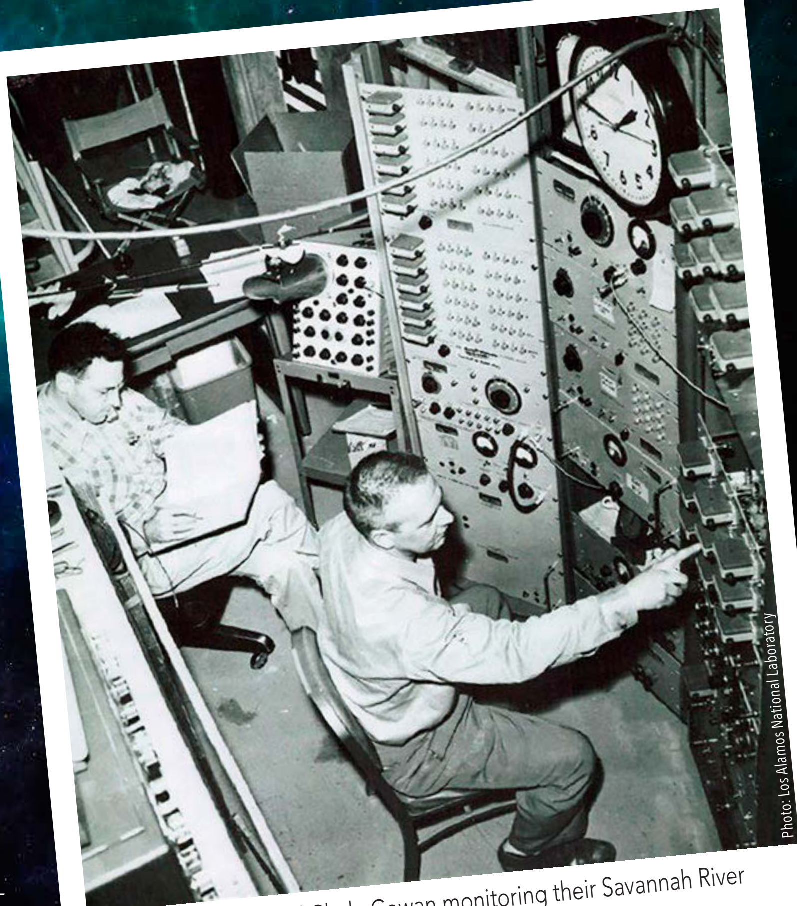
Photo: Los Alamos National Laboratory
Fred Reines, right, and Clyde Cowan monitoring their Savannah River experiment in 1956.

This was not an attractive prospect to most physicists, including Austrian physicist Wolfgang Pauli, who was a giant of the quantum revolution in the early 20th century. He is perhaps best known for the Pauli exclusion principle, which says that no two electrons can occupy the same bound state. He had an idea that energy conservation could be saved by invoking a new particle. The problem was that his hypothetical new particle seemed tailor-made to avoid any and all attempts at direct detection. First, it had no electric charge and very little, if any, mass. Second, the long half-life of most beta decay isotopes implied that its interaction strength would be incredibly weak. Even Pauli was daunted by his proposal, which he called a "desperate remedy." Its audacity was compounded by the fact that at that time, there were only two known subatomic particles: the proton and the electron.

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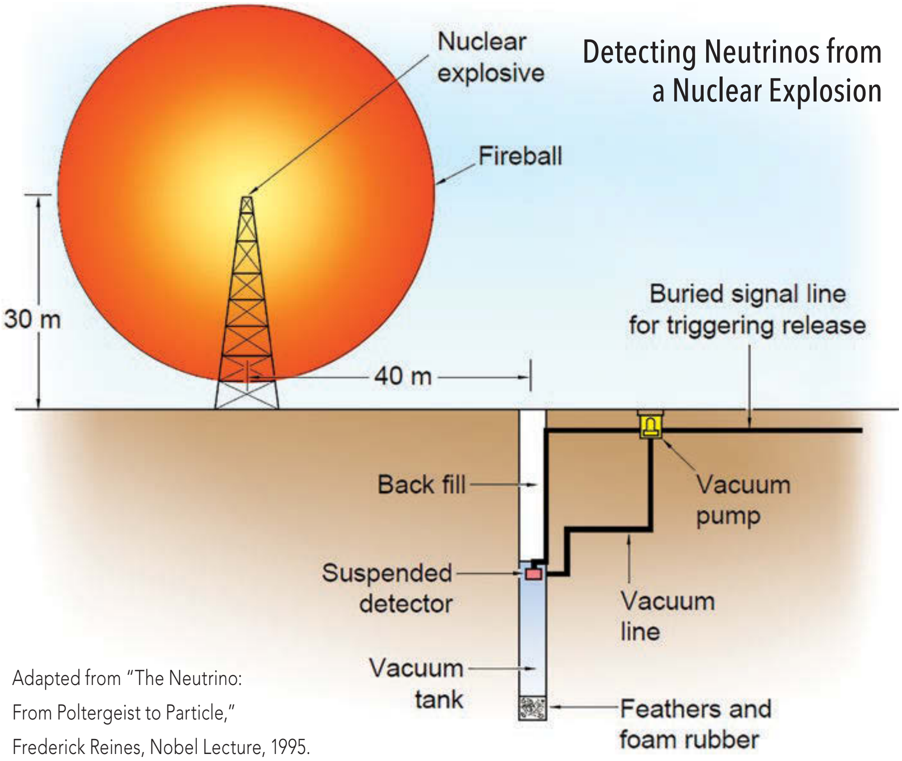

Adapted from "The Neutrino: From Poltergeist to Particle," Frederick Reines, Nobel Lecture, 1995.

Neutrinos and nuclear reactors

In a nuclear reactor, neutrinos come from the neutron-rich fission fragments that must beta decay to reach stability. Each of these decays produces a neutrino. For every gigawatt of thermal power, there are about 3×10^{19} fissions per second, and on average each fission results in six beta decays, so a gigawatt thermal reactor emits 2×10^{20} neutrinos per second. These neutrinos go out equally in all directions and stream freely through the reactor shielding. The intensity of neutrinos falls off with the square of the distance from the core. Reactor neutrinos are actually antineutrinos ($\bar{\nu}$), the antimatter counterpart to the neutrino, but in those early days, physicists were unsure if this distinction even existed.

Today, we know that there are at least three types of neutrinos associated with the electron and its heavier, short-lived cousins the muon and tau particles, and each has its own antineutrino. Since beta particles are electrons, beta decay involves electron neutrinos (ν_e). In fact, the neutrino type is defined by what it interacts with. At higher energies, there are processes that produce or destroy muon or tau particles, and these interactions involve the muon and tau neutrinos.

It wasn't clear how one would even attempt to detect this new particle. That is until 1934, when Enrico Fermi worked out the theory of nuclear beta decay. He used Pauli's new particle, calling it the neutrino—Italian for little neutral one—and representing it with the Greek letter nu (ν). In Fermi's model, the neutrino was an integral player in a new fundamental force that he called the weak nuclear force. Fermi cast beta decay as a simultaneous interaction of a proton, a neutron, an electron, and a neutrino. In this model, a neutrino could theoretically be detected through a kind of inverse beta decay in which it exchanges charges with a proton, morphing into a neutron and a positron. Still, the incredible weakness of the neutrino's interaction caused many physicists to despair that it could ever be observed. A neutrino from a typical beta decay would have an even chance of passing through a light-year of lead without interacting.

Throughout the 1930s, the neutrino remained an academic curiosity. To have a chance of observing Pauli's elusive new particle would require a powerful source that just didn't exist. Then World War II came along, putting a stop to international scientific collaboration, as physicists across Europe and the United States were diverted into secret war efforts such as the Manhattan Project. Indeed, it was the Manhattan Project that planted the seed for Reines and Cowan's eventual discovery. On November 16, 1942, Fermi led a team of scientists and engineers in creating the world's first nuclear reactor, Chicago Pile-1. With this invention, Fermi and company had created what is, still today, the best-known sustained source of neutrinos.

Still, in 1951, when Reines and Cowan got serious about searching for neutrinos, a reactor wasn't their first choice. Both men were working at Los Alamos and were involved in bomb testing, so, naturally, they proposed to search for neutrinos during a nuclear blast. The instantaneous fission rate could be thousands of times larger than in a reactor, and they figured that the intense pulse would help the signal stand out against backgrounds from environmental radiation. Of course, they would need to shield the detector from the intense conventional radiation of the nuclear blast, and for that they would have to go underground. To isolate the detector from the blast shockwave, they worked out a complicated system that involved their detector free falling down an evacuated shaft and landing in a bed of feathers (see above figure).

Ultimately, Reines and Cowan realized that the key to the measurement was a background-busting trick known as a delayed coincidence trigger. If they chose a hydrogenous material as their target, an antineutrino interacting with a hydrogen nucleus, or proton, via inverse beta decay, produced a neutron and a positron, resulting in two signals in delayed succession.

$$\bar{\nu}_e + p^+ \rightarrow n + e^+$$

The positron makes a prompt signal in the detector, while the neutron thermalizes and is captured by a nucleus. The neutron capture is delayed relative to the positron. This coincidence of signals could be used to filter out the vast majority of environmental backgrounds. The delayed coincidence trigger worked so well that Reines and Cowan realized that they could abandon their convoluted plans for a bomb blast and instead use a much simpler setup in the continuous neutrino flux of a nuclear reactor. This had the added advantage, as Fermi pointed out, that they could reuse their detector.

Early neutrino detectors

Reines and Cowan's first detector was a tank of organic liquid scintillator ringed with light-sensitive photomultiplier tubes. Organic scintillators have plenty of hydrogen targets for the neutrinos to interact with, and they emit light in proportion to the energy deposited by ionizing radiation. Their scintillator was doped with a cadmium compound to enhance neutron capture. This device was surrounded with alternating layers of lead and plastic to shield gammas and neutrons from the reactor, and it was installed near one of the Hanford reactors. Unfortunately, this detector was beset with backgrounds, most likely from cosmic ray neutrons, which can recoil off of a proton in the scintillator, mimicking the positron, and then thermalize and capture. Nevertheless, they saw slightly more delayed coincident events when the reactor was on compared to when it was off. Encouraged by this result, they went back to the drawing board in search of a better way.

Today, physicists have many ways to detect neutrinos from a wide range of sources: particle accelerators, the sun, cosmic ray interactions in the upper atmosphere, distant supernova explosions, and even beta decays from radioactive isotopes in the earth's crust. These experiments are never easy. To overcome the extreme improbability of any one neutrino's interaction requires a combination of large detectors, powerful sources, and long exposure times. Think of a neutrino experiment as a search for needles in a haystack. This trio increases the number of needles, but it also grows the haystack. Reines and Cowan needed a way to get rid of the hay.

Reines and Cowan weren't alone in their pursuit of the neutrino. Ray Davis, a nuclear chemist at Brookhaven National Laboratory, had a different detection method and a ready flux of neutrinos from the Brookhaven reactor. Davis used a radiochemical approach, in which neutrino interactions convert a stable nucleus into an unstable nucleus that can be easily separated and held in a detection chamber to be counted when it decays. Davis used a large tank of dry-cleaning fluid, carbon tetrachloride, to search for neutrino interactions that convert chlorine-37 to argon-37, which was extracted by bubbling helium through the fluid. Unfortunately for Davis, this reaction is only sensitive to neutrinos, and his attempts to detect reactor antineutrinos failed.

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The MicroCHANDLER detector is a prototype of a robust and mobile surface-level reactor neutrino detector. It uses high segmentation and a distinct neutron tag to reject backgrounds from cosmic ray fast neutrons.
Photo: Jonathan Link, Virginia Tech

Neutrino oscillations

In 1968, Davis successfully used his technique to observe neutrinos from the sun, showing that nuclear fusion is the source of the sun's energy. He would eventually be awarded the Nobel Prize for his discovery, but not before sparking a decades-long controversy known as the solar neutrino problem. The solar models predicted that Davis would observe three times more neutrinos than he did.

Particle physicists questioned the accuracy of the solar models, solar physicists questioned our understanding of neutrinos, everyone questioned Davis's experiment, but there was another possibility: The different neutrino types could be mixing over long distances in a phenomenon known as neutrino oscillations. Neutrino oscillation was a then hypothetical phenomenon that could occur if the neutrinos had mass, but the very successful Standard Model of particle physics was built on assuming that the neutrinos were massless.

The solar neutrino problem persisted for three decades, propelling research into both neutrinos and the sun. It was finally resolved in 1998 by a group of researchers in Japan who were watching a huge tank of ultra-pure water, buried deep underground, waiting to see if any of its protons would decay. They are still waiting. To pass the time, they took on a side study of atmospheric neutrinos looking for a telltale sign of neutrino oscillations.

Atmospheric neutrinos are produced when cosmic rays strike the upper atmosphere, creating showers of particles, many of which will ultimately decay into neutrinos. These neutrinos, including both electron and muon types, stream through the Earth, like light through glass, and can be detected coming from all parts of the sky, including the sky on the opposite side of the Earth.

When they looked at the neutrinos coming from above their detector, all was as expected, but for the neutrinos coming from below, the number of muon neutrinos was only half of what they expected. From the upper atmosphere, on the near side of the earth, to the upper atmosphere on the far side, the range of distances traveled by the neutrino arriving at the detector spans from 30 km to 13,000 km. The pattern of this muon neutrino deficit, as a function of distance traveled and neutrino energy, matched the expectation for neutrino oscillations.

Although muon neutrinos are not the same as the electron neutrinos coming from the sun, neutrino oscillations instantly became the leading hypothesis to explain the solar neutrino problem. The discovery of neutrino oscillations showed that the neutrinos indeed have tiny masses (less than one-millionth of the electron mass) and that neutrino mass meant that all types of neutrinos were likely to oscillate.

In this neutrino oscillation scenario, the sun produced the expected number of electron neutrinos, but by the time they reached Davis's detector, two-thirds would morph into muon or tau neutrinos. Davis's detection method was blind to these types, and so two-thirds of the neutrinos had effectively disappeared. In 2002, this hypothesis was confirmed by an experiment in Canada that was sensitive to solar neutrinos in two independent ways: one that sees only electron neutrinos, like those produced in the sun, and another that is equally sensitive to all three types. The results showed that the rate of interactions from all neutrino types was consistent with the prediction of the solar fusion model, while the rate of electron neutrinos matched that of the Davis experiment.

The leaders of the Japanese and Canadian projects shared the 2015 Nobel Prize in Physics for their discovery of neutrino oscillations. Their findings launched neutrinos to the forefront of particle physics, spawning dozens of new experiments and a flurry of theoretical activity. In both the United States and Japan, accelerator-produced neutrino beams were used to confirm the atmospheric neutrino findings under controlled conditions. Reactor experiments were used to measure key parameters, like the differences between the neutrino masses, which control the oscillation frequencies, and the strength of the mixing, which governs the oscillation amplitude.

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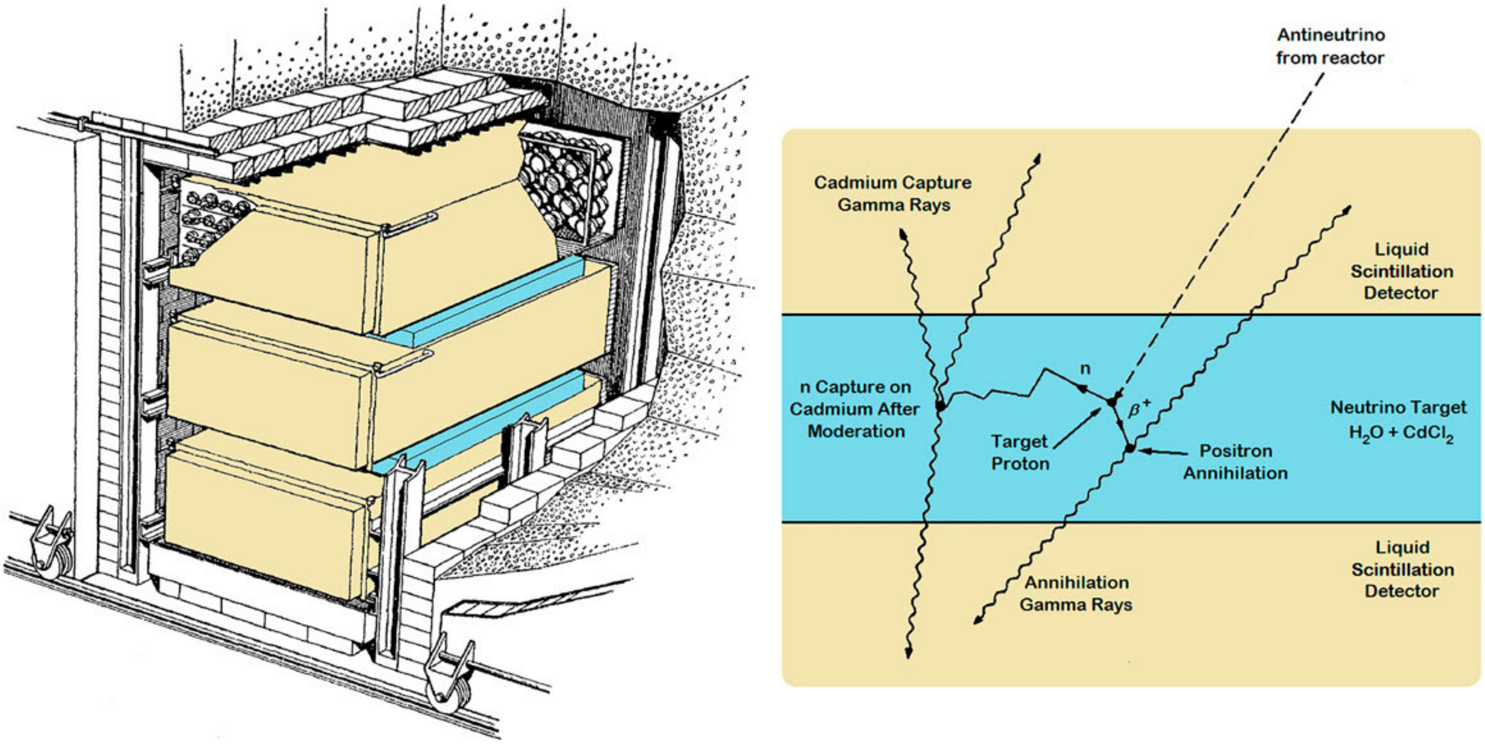
Graduate student Tulasi Subedi works with the MiniCHANDLER prototype housed inside Virginia Tech's Mobile Neutrino Lab. Photo: Jonathan Link, Virginia Tech



Sketch of the detector used by Reines and Cowan for their Savannah River project. When an electron antineutrino interacts in the water target via the inverse beta decay process, it can be detected by a succession of two gamma ray bursts that are observed in the liquid scintillation detectors above and below. Adapted from "Detection of the Free Antineutrino," F. Reines et al., *Physical Review* 117, 159, 1960.

The Savannah River project

In 1955, Reines and Cowan were optimistic that they were seeing neutrinos, but their hint of an excess wasn't strong enough to claim the discovery. Cosmic ray neutrons had obscured their quarry. To solve this problem, they took a two-pronged approach.

First, shield the neutrons. To accomplish this, they would move their project to a powerful new reactor at the Savannah River Site in South Carolina. There they found a well-shielded space, only 11 meters from the core but 12 meters underground.

Second, change the detector to focus on the unique characteristics of the positron. A recoiling proton from a fast neutron interaction will leave its kinetic energy in the scintillator just as a positron would, but that's not the end of the story for a positron. Being the antimatter counterpart of an electron, a positron stopped in matter won't survive for long. It quickly finds an electron and annihilates with it, emitting two back-to-back gamma rays, each with an energy equal to the electron mass.

Reines and Cowan's new detector was stacked like a club sandwich. The "bread" layers were three liquid scintillation detectors, and the "meat" layers were two water-filled neutrino targets (see above figure). In this design, the initial products of the inverse beta decay were not intended to be detected directly. The water targets weren't even instrumented. Instead, the positron would be detected by the coincident observation of the two annihilation gammas in the scintillation detectors on either side of the target. Similarly, the neutron was to be tagged by the gammas from neutron capture. The water was doped with cadmium to enhance this process.

This new detection method was very efficient, but it was very unlikely to be faked by a fast neutron. The combination of the shielding and the sandwich detector was like setting fire to the haystack of background. All that was left to do was sift through the ashes to find the neutrinos.

What reactors have taught us about neutrinos

Following the legacy of Reines and Cowan, the history of neutrino experiments at nuclear reactors has been long and productive. Dozens of reactor neutrino experiments have been mounted since their groundbreaking discovery. Many were searching for evidence of neutrino oscillations years before their discovery. Not knowing anything about possible oscillation frequencies or amplitudes, these experiments were shots in the dark, but after the discovery of atmospheric neutrino oscillations, reactor neutrino experiments finally had a specific question to address: If muon neutrinos are mixing, what are they mixing into?

In particle interactions, time reversal is an almost[1] perfect symmetry, which means that if muon neutrinos mix into electron neutrinos, then electron neutrinos must mix into muon neutrinos. Atmospheric neutrino experiments don't tell us which type of neutrino the muon neutrino oscillate into, but they do tell us where to look for an associated electron neutrino disappearance. Reactor neutrinos have lower energies, so the first oscillation maximum should correspond to a distance of 1 to 2 kilometers from a reactor.

Within the past 10 years, experiments operating in France, Korea, and China have succeeded in detecting this process. They observe an electron neutrino disappearance corresponding to about 10 percent of the missing atmospheric muon neutrino, which means that the other 90 percent should be oscillating into tau neutrinos. The first and most sensitive of these projects was a U.S.-Chinese collaboration located at the Daya Bay nuclear power plant in China.

Reactor neutrinos are also subject to solar neutrino oscillations, which occur over a distance scale that is 30 times longer than atmospheric. Still, the solar oscillation length is small compared to the region in the sun's core, where fusion takes place. As a result, solar neutrinos experiments can't make a very precise measurement of the oscillation length, but reactor experiments can.

In the early 2000s, an ambitious Japanese experiment called KamLAND used neutrinos from the 69 reactors across Japan and South Korea to study solar neutrino oscillations. With an average distance of 88 kilometers, they were sensitive to the first solar oscillation maximum, which appeared as a dip in their neutrino energy spectrum.

1 The tiny defect in time reversal symmetry, which is equivalent to the more commonly cited defect in charge/parity (or CP) symmetry, is responsible for the dominance of matter over antimatter in our universe. Without it, matter and antimatter would have been annihilated shortly after the Big Bang, and our universe would consist of pure energy.

Reactor neutrinos have generated mysteries and anomalies of their own. Theoretical calculations of the reactor neutrino detection rate chronically overpredict observations by about 6 percent. This phenomenon has been observed in more than 20 experiments spanning nearly 40 years. Drawing on a comparison to the solar neutrino problem, it's tempting to interpret this reactor antineutrino anomaly as a new type of oscillation occurring over very short distances, but for that interpretation to be correct, a new fourth type of neutrino would be required.

Even today, when fundamental subatomic particles number in the dozens, finding a new particle would still be considered a significant discovery, but, as a proposal, it's hardly as audacious as Pauli's manifestation of the neutrino to a scientific community that knew only two other particles. Yet, in one regard, this proposal is a match to Pauli's: Such a fourth neutrino may well be impossible to detect directly. To be consistent with all other well-established data, this fourth neutrino must not interact, even via the weak nuclear force. Its only connection to the visible world would be through oscillations with the other three neutrinos. To reflect its noninteracting nature, this hypothetical fourth neutrino is known as a "sterile neutrino."

Novel neutrino detectors

Currently, there are more than a half dozen experiments planned or under way to search for sterile neutrinos at reactors in the United States, Europe, and Asia. The goal is to find the telltale wiggles of an oscillation that may now be hidden within the observed deficit. This requires getting detectors as close to the reactor as possible. Since most reactors are not deep underground, these detectors must be designed to overcome the background levels at surface or in a near-surface environment, and that's yet again driving innovation in detector technology.

Neutrino researchers have long thought that neutrinos may find applications in reactor instrumentation. Neutrinos stream freely from the core, carrying information about the reactor power, the spatial distribution of fission, and the mix of fissile isotopes. If the detectors are sensitive enough, these signs can be read from well outside the facility, meaning that these measurements can be done without affecting site operations. In a recent study, the Daya Bay Reactor Neutrino Collaboration extracted the isotope-specific spectra from uranium-235 and plutonium-239 by using burnup information provided by the operators. In the future, this process can be reversed

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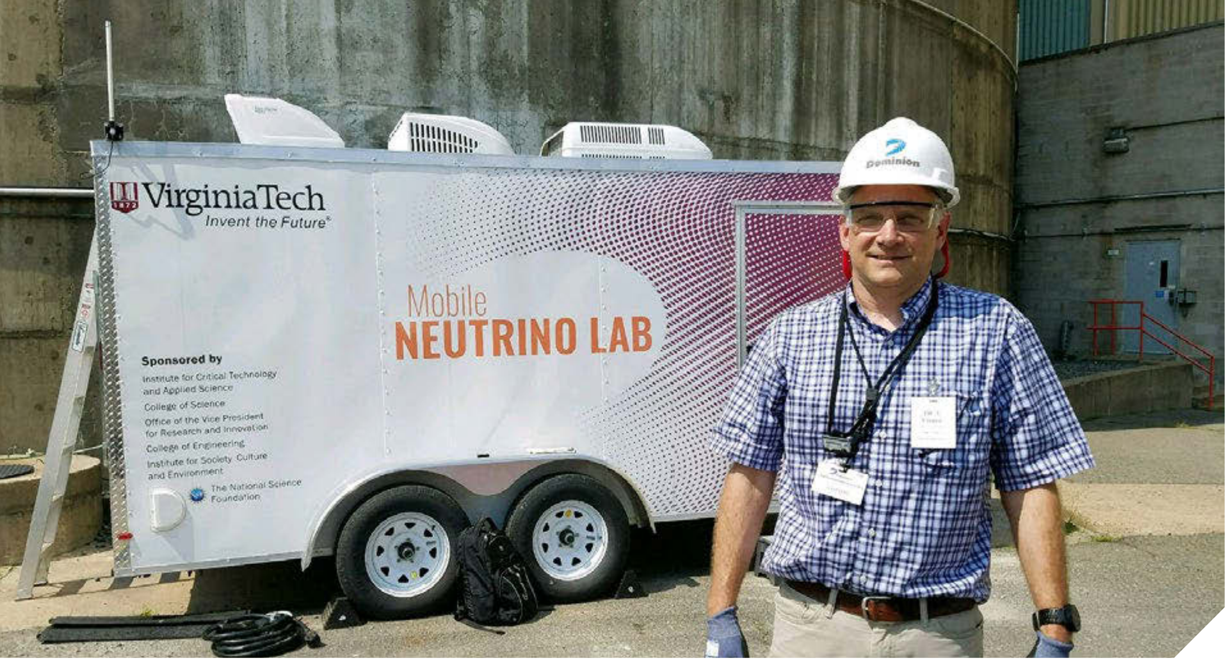

The MiniCHANDLER prototype detector deployed outside Unit 2 at Dominion Power's North Anna Generating Station in Mineral, Va. Photo: Steve Mackay, Virginia Tech

to extract the burnup information from the neutrino spectrum.

As the thinking goes, nuclear nonproliferation safeguards, which can be an adversarial process, are a promising first application for neutrino detectors. Other applications that have been discussed include instrumentation for advanced reactors, post-incident criticality monitoring, and spent fuel characterization. These discussions are mostly being had among physicists, but physicists are not in the best position to judge the needs of the nuclear industry. The National Nuclear Security Administration has commissioned a study of possible applications of reactor neutrino detection (nutools.ornl.gov) that is initiating discussions between physicists and the nuclear industry.

CHANDLER technology and the nuclear industry

Virginia Tech's Center for Neutrino Physics is one of many groups around the world working to develop robust and reliable reactor neutrino detector technologies that may soon be suitable for a whole host of applications in nuclear instrumentation and nuclear security. Virginia Tech's CHANDLER technology uses a highly segmented array of plastic scintillating cubes to tag the positron annihilation gammas, along with a distinct neutron tag, to tame the backgrounds in much the same way that Reines and Cowan did, while at the same time maintaining excellent sensitivity to the spectral information that is essential for nearly all applications.

In the summer of 2017, Virginia Tech's 80-kg prototype detector, known as MiniCHANDLER, was deployed at Dominion Power's North Anna Generating Station, outside the secondary containment building of Unit 2. Data were gathered for four-and-a-half months, spanning the fall refueling outage. With that data, a neutrino energy spectrum was extracted, comprising nearly 3,000 events. This demonstration represented the first detection of neutrinos with a mobile detector and the first observations of the reactor neutrino energy spectrum with an unshielded surface-level detector. All of this was achieved with one of the world's smallest neutrino detectors. (For details, see Haghighat et al., "Observation of Reactor Antineutrinos with a Rapidly Deployable Surface-level Detector," *Physical Review Applied* 13, 034028, March 2020.)

Research and development of the CHANDLER technology is ongoing for use in the search for sterile neutrinos and for applications to the monitoring and safeguarding of nuclear reactors. The technology is mature enough for engagement of the nuclear industry and the nuclear engineering community on the following questions: What are the needs for new instrumentation, particularly related to the advanced reactors that are now under development? What can we learn from a real-time noninvasive measurement of reactor burnup, and how can it be applied to improve reactor efficiency, reactor safety, or nuclear safeguards? What level of precision is required to make such measurements useful?

Recognition

By the late spring of 1956, Reines and Cowan were convinced that their search was a success. They saw four signal events for every background event, and the rate of neutrino events was consistent with the prediction from Fermi's theory of the weak interaction. Pauli's desperate remedy had been established as a fact of nature. It was time to let the world know.

Wolfgang Pauli received Reines and Cowan's telegram while attending a conference at CERN, the European Organization for Nuclear Research. He interrupted the proceedings to share the news. That evening, Pauli and some friends consumed a case of champagne in celebration.

On October 12, 1995, Fred Reines received an early morning call from the Royal Swedish Academy of Sciences, informing him that he had won the Nobel Prize in Physics. It took 26 years for Pauli's neutrino to be discovered and another 39 years for the Nobel Committee to recognize the achievement. Unfortunately, Clyde Cowan did not live to see this recognition.

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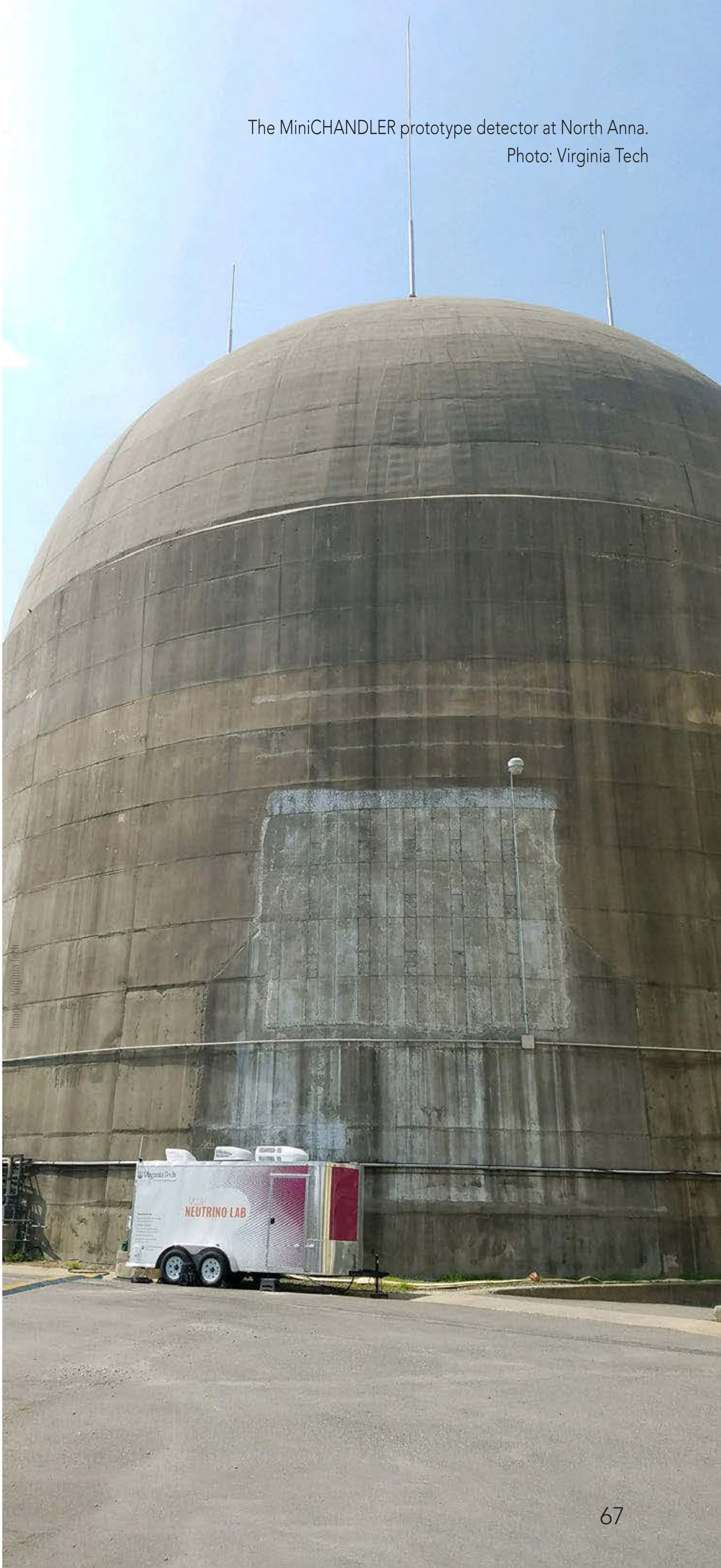

The MiniCHANDLER prototype detector at North Anna.
Photo: Virginia Tech