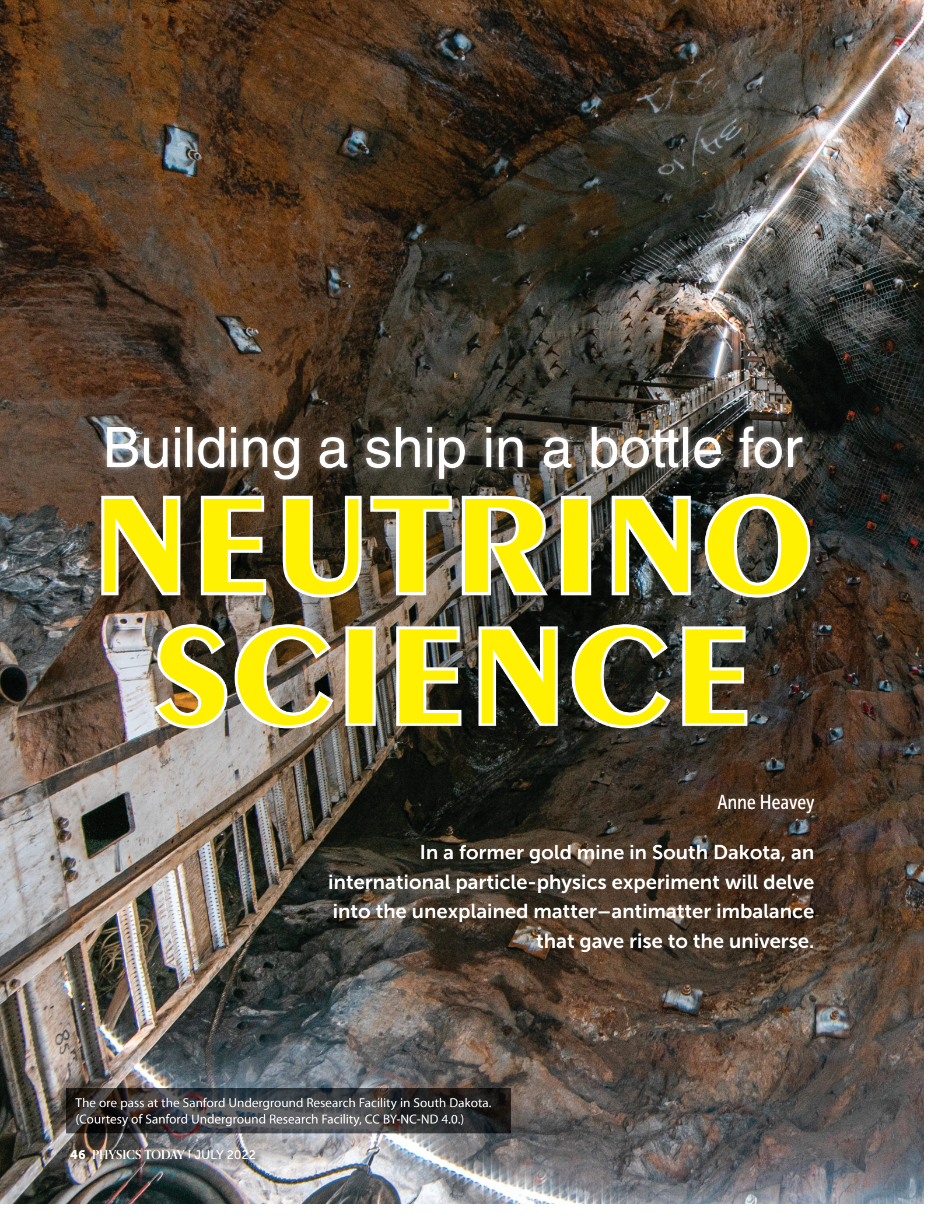




# Building a ship in a bottle for **NEUTRINO SCIENCE**

Anne Heavey

In a former gold mine in South Dakota, an international particle-physics experiment will delve into the unexplained matter–antimatter imbalance that gave rise to the universe.

The ore pass at the Sanford Underground Research Facility in South Dakota.  
(Courtesy of Sanford Underground Research Facility, CC BY-NC-ND 4.0.)



Anne Heavey is a senior technical editor at the Fermi National Accelerator Laboratory in Batavia, Illinois.



**T**he Deep Underground Neutrino Experiment (DUNE) will be the world's largest cryogenic particle detector. Its aim is to study the most elusive of particles: neutrinos. Teams from around the world are developing and constructing detector components that they will ship to the Sanford Underground Research Facility, commonly called Sanford Lab, in the Black Hills of South Dakota. There the detector components will be lowered more than a kilometer underground through a narrow shaft to the caverns, where they will be assembled and operated while being sheltered from the cosmic rays that constantly rain down on Earth's surface.

For at least two decades, the detector will be exposed to the highest-intensity neutrino beam on the planet. The beam will be generated 1300 km away by a megawatt-class proton accelerator and beamline under development at Fermilab in Batavia, Illinois. A smaller detector just downstream of the beamline will measure the neutrinos at the start of their journey, thereby enabling the experiment's precision and scientific reach.

### A whale of a problem

Imagine the following picture proposed by André de Gouvêa, a physicist at Northwestern University: atoms so big that each of their protons and neutrons is the size of a blue whale. Along with a pod of whales as a nucleus, he chose rabbits as the electrons. In a volume filled with the whale-rabbit element—whimsically named *cetaceacuniculum* by borrowing from the Latin words for whale and rabbit—each atom would be tens of thousands of kilometers across. Neutrinos, on the other hand, would be but fruit flies passing through, unaware of and unaffected by the other objects in the vast, largely empty space. So how do we even know neutrinos exist? Furthermore, why do we think they might be of any importance?

The existence of neutrinos has been demonstrated by many experiments, and particle physicists have been steadily accumulating clues about the neutrino's role in the domination of matter over antimatter in the early universe (see *PHYSICS TODAY*, June 2020, page 14). DUNE researchers are developing and testing ever-more-sensitive and high-precision technologies to understand and elucidate how the neutrino may have been instrumental at that crucial juncture.

DUNE and its associated home, the Long-Baseline Neutrino Facility (LBNF), are hosted by Fermilab and make up the LBNF/DUNE megaproject. DUNE brings together more than 1300 scientists and engineers from more than 30 countries. LBNF/DUNE is conceived around three instruments: a megawatt-class proton accelerator and beamline at Fermi-

lab that is engineered to generate what will be the highest-intensity neutrino beam ever built and two ultrasensitive detectors to pick up neutrinos' signals and measure their properties. The near detector will be constructed at Fermilab, just downstream of the beamline. The far detector will reside at Sanford Lab. The LBNF/DUNE baseline—the separation between the neutrino source and the far detector—is 1300 km (see figure 1).

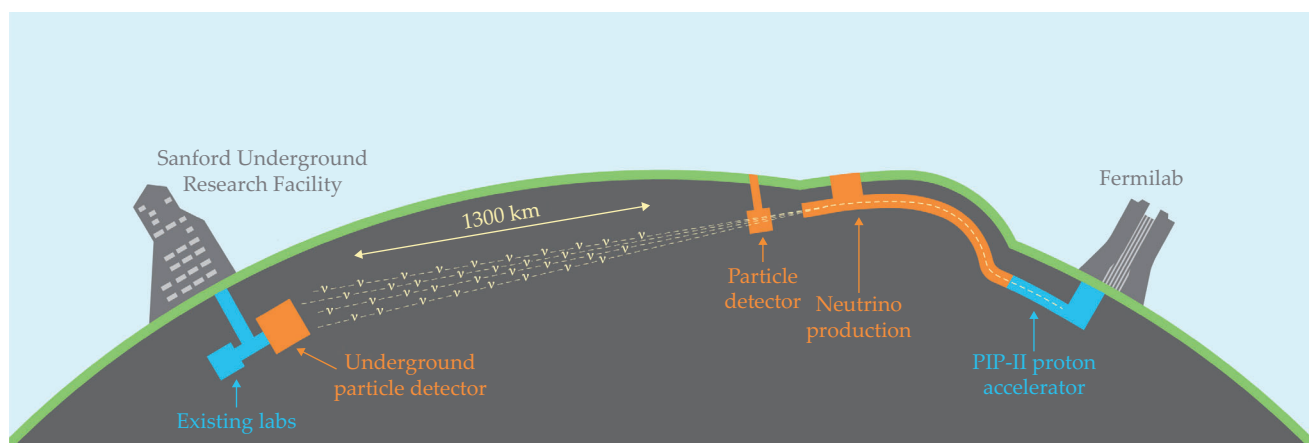
Launched in early 2015 and built on designs developed for two earlier projects,<sup>1</sup> DUNE is scheduled to start taking data in the late 2020s. While some researchers are preparing for the physics studies themselves, other members of the LBNF/DUNE enterprise are wrestling with practical complications: the experiment's sheer scale, the delicacy and precision of its components, the decade-plus duration required for construction, and the logistics of moving items and people around the world. Some of the challenges are unique to LBNF/DUNE, whereas others are shared, at least to a degree, by other neutrino experiments and even more broadly across high-energy physics. The fact that DUNE will proceed despite those challenges conveys the importance that scientists place on understanding the universe's fundamental properties.

### A mysterious asymmetry

It is not obvious that neutrinos—or people, for that matter—should be here at all. If just after the Big Bang the still-tiny universe contained equal amounts of matter and antimatter, why didn't it simply self-destruct? If every matter particle were the perfect mirror image of its antiparticle, with opposite charge and reversal of left and right, the mutual annihilation should have been complete.

Some aspect of the matter-antimatter symmetry must therefore not be working as expected. The unanticipated behavior, without which matter could not have beat out antimatter, requires that nature violate charge conjugation-parity (CP) symmetry, which says that the laws of physics must act the same on a particle whose charge is reversed and





**FIGURE 1. A NEUTRINO BEAM** traveling from Fermilab in Illinois to the Sanford Underground Research Facility in South Dakota lies at the heart of the Deep Underground Neutrino Experiment. Two detectors set 1300 km apart will look for oscillations between neutrino states. (Adapted from an illustration courtesy of Fermilab.)

whose coordinates are inverted. Particle-physics experiments have found *CP* violation in processes involving quarks, but not to a level that would account for the extraordinary matter-antimatter asymmetry in the universe today—at least not according to the standard model in its current form.<sup>2</sup> So what else might contribute to the asymmetry?

Leptons—non-quark-based particles that include electrons, muons, and neutrinos—might be the culprits. Paramount among DUNE's potential discoveries is evidence of *CP* violation in the lepton sector, which could indicate that neutrinos hold the key to the matter-antimatter symmetry.

Neutrinos were postulated by Wolfgang Pauli in 1930 to solve an apparent breach of energy-conservation laws in radioactive decays. A quarter century later, the first of what turned out to be three types, or flavors, of neutrinos was discovered (see figure 2). Subsequent experiments revealed all three flavors, each of which corresponds to a charged lepton, and they showed that a neutrino can transform from one flavor into another as it travels. The process, known as oscillation, occurs over a wide range of distances and depends on the energy of the source neutrinos (see *PHYSICS TODAY*, December 2015, page 16). The LBNF/DUNE beamline is designed to produce neutrinos that span the energy range of a few hundred MeV to a few GeV and that oscillate over more than a thousand kilometers, corresponding to the experiment's baseline.

The physics behind neutrino oscillations implies that each neutrino flavor state is a mixture of three mass states. The determination in 1998 that the neutrino—assumed massless, and in fact defined as such for decades—definitively has mass was one of the most important fundamental particle-physics discoveries of the late 20th century.<sup>3</sup>

## Tiny escape artists

Neutrinos, so named because they are electrically neutral, have the smallest masses of the pantheon of elementary particles. They interact with matter only through gravity and the weak nuclear force. Weak interactions have a strength about one-tenth of a trillionth that of electromagnetic ones, and they're best known as a mechanism for radioactive decay.

Because neutrinos encounter little if any resistance, they are the first particles to escape from deep inside active stars, collapsing stars, and, originally, the Big Bang. They travel through the universe virtually unimpeded, carrying information that no other particles can. For example, in 1987, the Kamiokande-II experiment in Japan captured a telltale spray of neutrinos escaping from a supernova.<sup>4</sup> (See the article by Masa-Toshi Koshihara, *PHYSICS TODAY*, December 1987, page 38.) Study of that signal has led to a greater understanding of supernova dynamics—one that DUNE hopes to build on.

It's clear that observing enough neutrino interactions to make definitive discoveries requires a huge detector mass. Also necessary are copious neutrinos, a long data-collection period, and sensitive detection elements. Furthermore, no known technology can directly detect a neutrino; experiments rely on gathering enough information from particles created in each neutrino interaction to reconstruct that interaction and tease out evidence that a neutrino initiated it. That process requires a detailed understanding of the sought-after experimental signatures: the unique products of physically allowed decays in concert with the detector elements' responses.

When a neutrino interacts with a target particle via the weak force, the two particles exchange either a neutral  $Z^0$  or a charged  $W$  boson.<sup>5</sup> In the exchange of a  $Z^0$ , the neutrino transfers some of its energy to the target particle and continues on, accompanied by other particles created in the collision.

If the energy of the incoming neutrino is high enough, though, it can exchange a  $W$  boson with the target particle. In that case it transforms into its detectable partner lepton—an electron, muon, or tau—and acquires a charge in the process. The transformation requires the incoming neutrino's energy to be somewhat higher than the rest mass of its partner lepton: more than 0.5 MeV for an electron, roughly 50 MeV for a muon, and several GeV for a tau. The target particle's charge also changes, in observance of charge-conservation laws, which effectively changes it into a different particle. Somewhere between 0 and 10 secondary particles are created out of the interaction's energy.

When a neutrino interacts with a nucleus, it may interact with the whole thing, with a single nucleon, or even with just one quark. The probability of each depends on the energy of the incoming neutrino. The particles produced in the collision can tell the story, but coaxing it out of them is one of the most significant challenges of neutrino physics.

A particle detector picks up, digitizes, and processes an as-



**FIGURE 2. THE COWAN-REINES EXPERIMENT** confirmed the existence of neutrinos in 1956. Clyde Cowan (far left) and Frederick Reines (far right) used large tanks of water to detect electron antineutrinos produced by a nearby nuclear reactor. (Photo from LANL/Science Source/Science Photo Library.)

semblage of signals in a time frame associated with a single interaction. Later, a set of reconstruction algorithms uses the data to work backward and determine the parameters of the interaction. The same is true for all particle experiments, but it presents a particular challenge for long-baseline experiments like DUNE, whose beamlines produce neutrinos in the 500 MeV–5 GeV range. Neutrinos with energies below that range tend to interact with the entire nucleus, whereas neutrinos above that range tend to interact directly with quarks. The transitional range used by DUNE, however, presents a complicated mix of interactions. Although the researchers would have preferred that the experiment operate in a more straightforward energy range, constraints on the baseline and the neutrino beam needed to achieve the physics goals forced researchers to work in that awkward transitional range.

## Beam building

You can't steer a neutrino. You can't push or pull one either. To create a neutrino beam, you need to start with another beam made of more controllable—that is, charged—particles, such as protons, and then accelerate them to nearly the speed of light and smash them into a target. That process creates oodles of other particles, many of which will decay into neutrinos.

At Fermilab, a chain of particle accelerators produces pulsed beams of relativistic protons grouped in tightly compressed bunches. To generate the high-intensity beam needed for DUNE, a new state-of-the-art superconducting accelerator, known as the Proton Improvement Plan-II or PIP-II, was in-

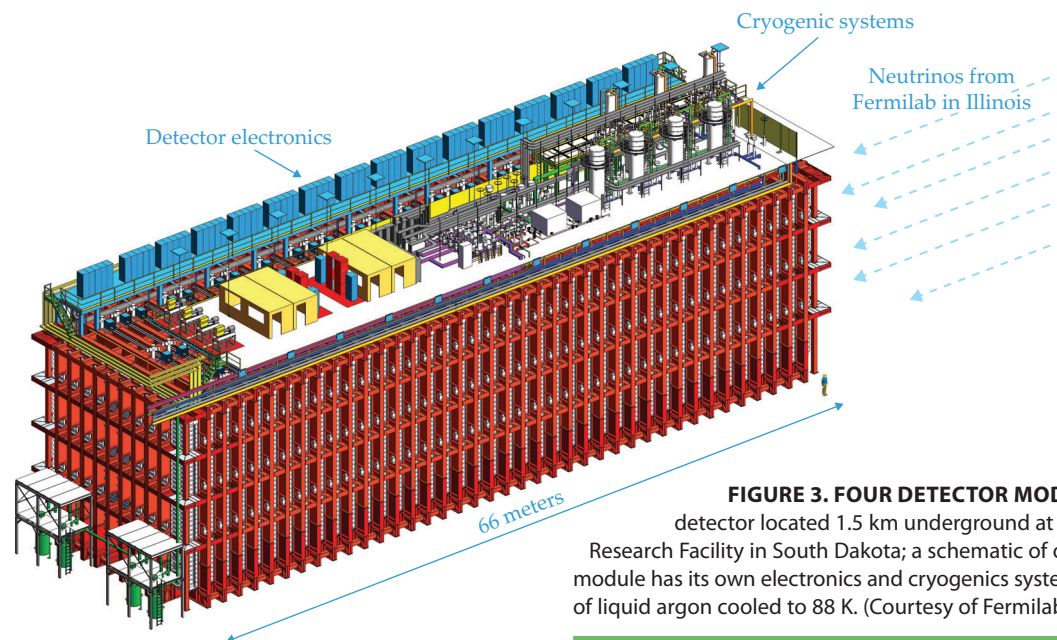
stalled at the start of the chain.<sup>6</sup> The protons head from there to the booster and the main injector, where they reach energies of 120 GeV. At that point, the new LBNF/DUNE beamline will extract protons, steer them toward the near and far detectors, focus and align the beam, and smash it head-on into a target the diameter of a pencil.

The charged particles created in the collisions will be tightly focused before they decay so they produce a narrow, intense neutrino beam in the direction the parent particles were steered—namely, toward the detectors. Other particles created in the decay get absorbed in tons of concrete and steel shielding. The shielding poses no barrier to the neutrinos because, recalling *cetaceacuniculum*, nothing really does. The vast majority of the neutrinos pass right through the near detector, through the 1300 km of earth, through the far detector, on through more earth, and finally out into space, oscillating the entire way. Only a tiny fraction will interact with the detectors.

Like neutrinos themselves, the challenges of designing and building neutrino experiments come in various flavors. Detectors are often located in quite inconvenient, if not downright inhospitable, places—for example, underneath mountains or deep in former mines—to shield them from sources of such unwanted interactions as cosmic rays. Because of the volume of material required, neutrino detectors have even been installed deep in the sea and at the South Pole (see, for example, *PHYSICS TODAY*, May 2013, page 14), where the surrounding water or ice serves as the target medium.<sup>7</sup>

Scientists have invented a host of neutrino detection methods





**FIGURE 3. FOUR DETECTOR MODULES** will make up the far detector located 1.5 km underground at the Sanford Underground Research Facility in South Dakota; a schematic of one is shown here. Each module has its own electronics and cryogenics systems to keep its 17 000 tons of liquid argon cooled to 88 K. (Courtesy of Fermilab.)

over the past several decades. They've built distinct types of detectors with various experimental goals as new discoveries have been made and new measurements have been sought that required different features and capabilities. To measure low-energy solar neutrinos, for example, a detector needs a low energy threshold. Astrophysical neutrino measurements typically require precise angular resolution. Beam neutrino-oscillation experiments like DUNE require an intense supply of neutrinos of a known flavor that travel a given distance; they also rely on excellent particle-identification and energy-measurement capabilities. Some à la carte features can be added to a detector, but the number that can be included in a particular experiment is limited.

Another aspiration of DUNE's is capturing a core-collapse supernova's neutrino burst—a roughly 10-second initial outpouring of neutrinos that precedes the collapse. To do so, the detector must be quite robust. It can't afford to be off-line for more than rare and brief maintenance periods because such a neutrino burst could come at any time. The detector must also be able to handle the data deluge that a supernova event would generate—potentially terabytes of data within a window of only a few seconds.

DUNE's far detector will be a liquid-argon time-projection chamber (LArTPC; see the box on page 51 for more about its principle of operation). LArTPCs are enormous vats of cryogenic liquid argon outfitted with components that generate an electric field across the liquid volume and elements for detection. When charged particles emerge from a neutrino interaction with an argon nucleus, they ionize other argon atoms, and the liberated electrons drift under the electric field's influence to a finely segmented collection plane. Also, because liquid argon is a profuse scintillator, electron detectors are usually supplemented with photosensitive elements for light detection.

The LArTPC's fine segmentation enables efficient distinction between actual signal events and uninteresting background interactions. Two key factors affect an LArTPC's performance: the purity of the liquid argon and noise on the readout elec-

tronics. Impurities, such as oxygen and water, tend to swallow up the drifting electrons, thereby attenuating the signal's charge over long drift lengths and reducing the signal strength. Noisy electronics reduce the signal-to-noise ratio, making it harder to separate the two.

## Down-to-earth challenges

Coveralls, helmet, boots, headlamp, check. It was October 2018 and I was ready to descend deep into the underground labyrinth of the former Homestake gold mine in Lead, South Dakota, now home to Sanford Lab and its ultrasensitive science experiments. It was here, starting in the late 1960s, that a team led by Ray Davis Jr, a physicist at Brookhaven National Laboratory, undertook the neutrino experiment that famously observed only a third of the electron neutrinos expected from the Sun.<sup>8</sup> That discovery bolstered the theory of neutrino oscillations initially proposed by Bruno Pontecorvo in 1957 and eventually led to two Nobel Prizes in Physics. A share of the 2002 prize was split by Davis and Masatoshi Koshiba for their initial detections of cosmic neutrinos; the other was shared by Takaaki Kajita and Arthur McDonald in 2015 for conclusively demonstrating the phenomenon. Tagging along with a group of visiting particle physicists, I would get a glimpse of the historic site being prepared for DUNE.

The spaces for the DUNE far detector at Sanford Lab, which is planned to include four LArTPC modules (see figure 3), require excavation of about 800 000 tons of rock—or the equivalent mass of about eight aircraft carriers, as Chris Mossey, a retired US Navy admiral and now LBNF/DUNE-US project director, likes to describe it. The excavation at Sanford Lab will create two detector caverns, each three stories high and 145 m long that will house two modules, and a central utility cavern 190 m long. The total volume is around 250 000 cubic meters, the equivalent of about 100 Olympic-size swimming pools. Cavern excavation began in spring 2021 following an extensive renovation of the 1930s-era Ross Shaft—the same shaft my companions and I used on our visit—that connects the



underground site to the surface at Sanford Lab. Rock travels up the 4 m × 6 m shaft and then along a newly constructed conveyor that deposits it into a large, open former mining area.

The reasons for choosing that location include the geo-technical strength of the rock at the underground site, the capacity of the Ross Shaft elevator, constraints on excavation so deep underground, and the internal and external forces that act on an insulated steel container, called a cryostat, filled with a heavy liquid. Each module will be assembled of still smaller detector elements that will fit either in or under the 4 m × 1.5 m cage or in one of the two roughly 1.5 m × 1.2 m skip compartments in the shaft. The detector's construction is reminiscent of a ship in a bottle. Together the four modules will contain nearly 70 000 metric tons of liquid argon. At least 40 000 metric tons will be in the instrumented, usable volumes of the LArTPCs from which data from particle interactions will be recorded and sent out to a data acquisition system.

## Keepin' it cool

Delivery, handling, and storage of the vast quantity of liquid argon required will take a few years and serious planning. Many questions needed to be answered, including the following: What is the total capacity of the vendors within trucking distance? How many tanker trucks will be needed, and over what period of time? How will the undertaking affect the local community? How will weather, or the annual Sturgis Motorcycle Festival, affect deliveries? What is the best way to transfer the argon underground? How much storage is needed in case a delay arises in preparing a cryostat?

The cryogenics team will likely need to coordinate three or four vendors that, together, will make about 1000 deliveries per detector module. The argon will arrive in 20-ton-capacity

tank trucks over a period of roughly a year. From the interstate highways, the trucks—at least 25 each week—will wend their way into the Black Hills, through the small town of Lead, and finally up a steep hill to the argon receiving station at the Ross Shaft headframe. To get a scale of the undertaking, add to that the delivery of cryostat and detector components, then multiply by four.

Transferring liquid argon at 88 K directly down the Ross Shaft would require insulated piping and a set of pressure stations along the way. Instead, equipment will vaporize the argon at the surface, send it down through uninsulated pipes, and recondense it underground.

Once a detector is fully installed inside a cryostat, the interior must be made free of all debris and loose material that could contaminate the argon. At that point, the cryogenics system will introduce the purified heavier-than-air argon vapor at the bottom so it can slowly push the air up and out. The purge will be repeated 10 times to reduce contamination levels in the cryostat and piping to a few parts per million before the cooldown can start.

To cool the cryostat volume, atomizing sprayers will introduce liquid argon at the top of the cryostat and let gravity and convection distribute it. When the interior reaches 90 K, the system will begin to fill the cryostat with purified liquid argon—a yearlong process during which the deliveries must keep up with the fill rate. Recirculation and constant purification processes kick in when the liquid depth reaches about 1.5 m. A minuscule but unavoidable heat ingress leads to a very slow, constant evaporation of the liquid, which, in turn, leads to the need for a continuous vapor recovery and reliquefaction process.

Those cryogenic processes, some of which must operate for the lifetime of the detector, call for an industrial-scale cryogenics

## LArTPC OPERATING PRINCIPLE

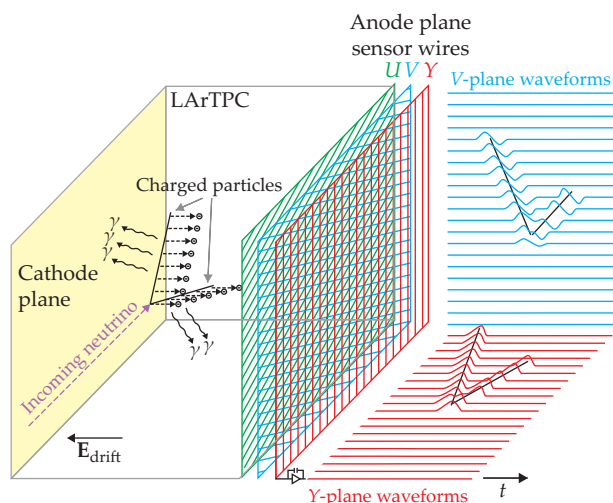
In its most basic configuration, a liquid-argon time-projection chamber (LArTPC) consists of a cathode plane (left) at a high negative voltage and a grounded anode plane (center) that is parallel to it and some distance away. Both are immersed in liquid argon, and together they establish an electric field across the liquid volume.

When a neutrino interacts with an argon nucleus, high-energy charged particles emerging from the interaction liberate electrons in the liquid argon. The electric field pushes the electrons toward the anode and draws the positive ions toward the cathode. The diagram, adapted from reference 9, depicts the DUNE design in which the anode is made up of planar arrays of sensor wires strung at different angles relative to each other; the wires in each plane are spaced a few millimeters apart.

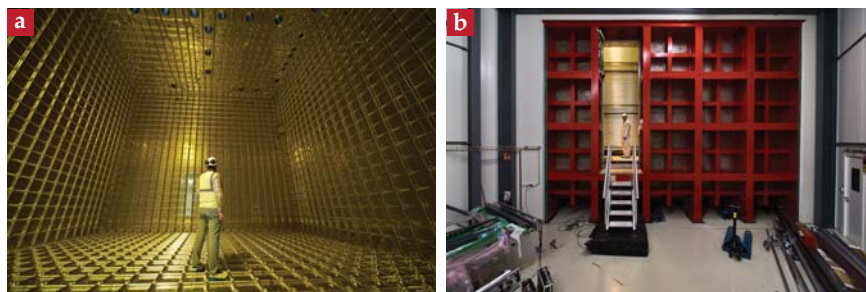
Just like any charge moving in the vicinity of a conductor, drifting electrons create signals on the induction plane wires, *U* and *V*, as they pass. Once the electrons reach the inner collection plane, *Y*, they produce signals on its wires, too, and are absorbed. The signals from the three wire planes are captured by the readout electronics. Photons produced in the interaction are also captured by a separate photon detection system and provide a time stamp for each event.

Specialized software processes the signals to reconstruct a

time-evolving stereo projection of the pattern produced on the wire planes (right) that reveals the location, time, and characteristics of the original neutrino interaction in the liquid. See reference 9 for more details.







**FIGURE 4. PROTOTYPE DETECTORS** built at CERN for the Deep Underground Neutrino Experiment were just 1/20th the size of the final planned detector, but when completed, they were the largest liquid-argon time-projection chambers ever made. **(a)** Prototype components were installed in this inner stainless-steel membrane and immersed in liquid argon. The gold color is an artifact of the lights used to protect the photon detectors during installation. **(b)** A red steel outer structure supports the multilayer insulated cryostat. (Courtesy of CERN/Maximilien Brice/Julien Marius Ordan.)

system. DUNE will not be a test bed for any of the systems; all those being implemented have been extensively tested and used in industrial environments. The creativity is in identifying solutions that are as standard as possible, meet the performance requirements, and—importantly—fit down the shaft.

All the components that go into a detector must be thoroughly tested under conditions similar to actual operating conditions. Furthermore, constructing, transporting, assembling, and installing precision components at the size and scale required for the DUNE detector modules requires careful planning and rehearsal. Prototyping has therefore been integral to DUNE's strategy for success. In addition to earlier, smaller prototypes, the DUNE collaboration has constructed and operated two 1/20-scale prototypes at CERN over the past three years (see figure 4). The prototypes used different LArTPC designs and were both instrumented with a small number of full-scale detector components. When installed in cubic cryostats nearly 6 m on a side, the devices became the largest LArTPCs built and operated to date, barely beating out the narrower ICARUS detector at Fermilab for the distinction.

The far-detector prototyping effort has validated the technology and the performance of the detection components in liquid argon, and it has demonstrated excellent control over argon purity and signal-to-noise ratio. Comparing the carefully choreographed assembly and installation of the prototype to a Fred Astaire dance number, installation of the full-size detector will require the team to execute the moves not just 20 times over for each of the four modules and 1450 m underground but, like his partner Ginger Rogers, backward and in high heels—down shafts, through excavated corridors, and around obstacles.

## The near detector

At Fermilab, just downstream of the neutrino source, the near detector—a smaller hybrid neutrino detector—will be installed in a shallow underground cavern. It is composed of three subdetectors, one of which is an LArTPC whose readouts can undergo apples-to-apples comparisons with those from the far detector. Together the far and near detectors allow the experiment to take full advantage of the 1300 km separation, which is optimal for observing *CP* violation through neutrino oscillations.<sup>1</sup> The near detector will provide information crucial to

interpreting the measurements made in the far detector and reducing their uncertainties, and it will also perform some independent physics studies.

Since the neutrino beam will be much narrower and therefore more intense at the near detector than at the far detector at Sanford Lab, both the LArTPC and a subdetector optimized for other studies will be able to move off the beam axis to sample different neutrino energy spectra in the beam and enable further comparisons. The third subdetector, a beam monitor, will measure variations in the beam via the products of the relatively copious neutrino interactions that take place in its volume. The beam monitor remains fixed in the beam path, where it is most sensi-

sitive to those variations.

When all three subdetectors are placed end to end along the beam axis, they fit into a space 50 m long, 19 m wide, and 10 m high—about a quarter the size required for one far-detector module. And, like the far detector, all the systems must undergo prototyping regimens, albeit at an appropriately smaller scale.

The far detector will need to collect a few thousand neutrino interactions to reach the measurement precision that will allow DUNE to accomplish its ambitious physics goals. Given the size of the far detector, the intensity of the neutrino beam, and the expected interaction rate, the experiment is planned to operate for about 20 years.

Many physicists will spend significant fractions of their careers devoted to DUNE during that time—monitoring the near and far detectors, fixing or upgrading things as needed, and analyzing the data. Accelerator physicists will keep the beam running smoothly. Many scientists, engineers, computing specialists, technicians, and project management professionals have already spent years planning and developing the experiment. Everyone involved is looking forward to witnessing the transformative discoveries that DUNE promises.

*I'd like to thank Steve Brice, Chris Mossey, Elizabeth Worcester, and David Montanari for particularly useful discussions in the development of this article.*

## REFERENCES

1. LBNE collaboration, <https://arxiv.org/abs/1307.7335>; L. Agostino et al., <https://arxiv.org/abs/1409.4405>.
2. M. K. Gaillard, P. D. Grannis, F. J. Sciulli, *Rev. Mod. Phys.* **71**, S96 (1999).
3. Y. Fukuda et al. (Super-Kamiokande collaboration), *Phys. Rev. Lett.* **81**, 1562 (1998); Y. Koshio, *J. Instrum.* **15**, C06041 (2020).
4. K. S. Hirata et al., *Phys. Rev. D* **38**, 448 (1988).
5. B. Abi et al., <https://arxiv.org/abs/2002.03005>.
6. M. Ball et al., *The PIP-II Conceptual Design Report*, Argonne National Laboratory and Fermilab (1 March 2017).
7. ANTARES collaboration, <https://antares.in2p3.fr>; IceCube Neutrino Observatory, <https://icecube.wisc.edu>.
8. R. Davis Jr, D. S. Harmer, K. C. Hoffman, *Phys. Rev. Lett.* **20**, 1205 (1968).
9. M. Diwan et al., *J. Phys.: Conf. Ser.* **762**, 012033 (2016).