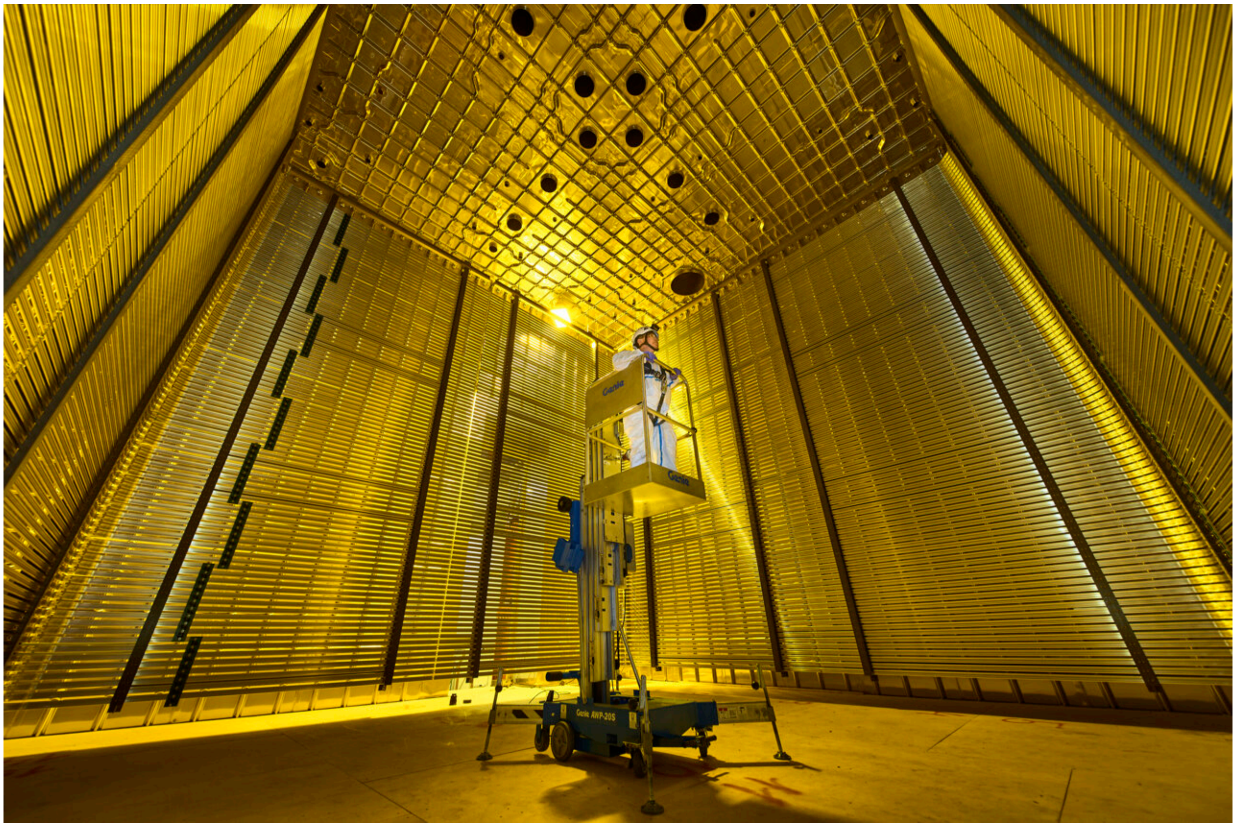
Unraveling the neutrino's mysteries at the Deep Underground Neutrino Experiment

January 5 2023, by Suzanne Irby



A look inside the ProtoDune Cyrostat Final structure inside a mine in South Dakota. Credit: CERN

Neutrinos mind their own business. Each second, billions of these fundamental particles will pass through stars, planets, buildings, and human bodies and will rarely ever be stopped by them, like a subatomic subway crowd. It's why they're often described as "ghostly" or "elusive."

If scientists could create and capture the rare instances when these tiny and weakly interactive particles run into something, they could step into the gray area that all physicists ultimately hope to explore, said theoretical physicist Patrick Huber: that of facts that exist outside the standard model of Particle Physics, beyond its explanation. Neutrinos live there, and so does dark matter.

Neutrino behavior, if accurately measured, could hold the evidence for how we—and our bodies and buildings and planets and stars, all made of matter—have been able to exist since the Big Bang. "There are certain things that the standard model does not explain, like why there's more matter than antimatter in the universe," said Huber, a professor in the Department of Physics and a Roger Moore and Mojdeh Khatam-Moore Faculty Fellow in the Virginia Tech College of Science. "But we never have found the ingredients which make these known facts outside of the standard model really work. If there is to be a large contribution of new physics, it can only really manifest itself in neutrinos."

To find out what neutrinos are up to, physicists will need to shoot them from the most powerful beam ever made at a distant, massive, subterranean, and painstakingly precise particle detector. More than a thousand scientists have come together to create that kind of experiment in a decades-long project called the Deep Underground Neutrino Experiment (DUNE), hosted by the U.S. Department of Energy's Fermi National Accelerator Laboratory, or Fermilab.

For the past decade and in the buildup to DUNE's development, Huber has collaborated with experimental physicist Camillo Mariani at Virginia Tech's Center for Neutrino Physics, where they've looked at ways to achieve the unprecedented precision an experiment like DUNE will need to measure neutrino behavior and discover the "new physics" sought by the field.

Mariani has brought what they've learned to his work on DUNE's international team as they develop the facility. Their pursuit of precision is one piece of a puzzle that Raymond Davis Jr. and John Bahcall started in the 1960s, with attempts to count solar neutrinos.

When two physicists stared up at the sun

Raymond Davis Jr. led one of the first experiments to measure neutrinos coming from one of nature's abundant sources: the sun. As Davis built the experiment at the Homestake Mine in Lead, South Dakota, Bahcall calculated the amount of solar neutrinos he predicted the experiment would collect from the nuclear reactions that took place inside its large, underground tank filled with cleaning fluid. But the Homestake Experiment, which ran from 1970–92, only collected one-third of the neutrinos Bahcall had predicted.

Most physicists at the time figured that either Davis had done something wrong with the experiment or that Bahcall's calculations were off. The issue of the missing neutrinos became known as the "solar neutrino problem" that physicists would try to solve for years. Scientists at the Sudbury Neutrino Observatory finally solved it in a 2002 experiment at a Canadian mine.

Using a giant sphere full of heavy water, they measured neutrinos via the light produced inside by nuclear reactions. They found the reason for the missing neutrinos: Neutrinos change type, or "flavor," as they fly through space.

There are three known neutrino flavors: electron, muon, and tau. The Sudbury experiment was sensitive to all three, unlike Davis's, which only picked up electron neutrinos. It's this phenomenon of changing flavors, known as "neutrino oscillation," that directly contradicts the standard model, which had predicted neutrinos to be massless.

Mariani breaks down neutrino oscillations using ice cream flavors. "You can imagine that you go to an ice cream shop, and you get your favorite: banana," Mariani said. "And then you step out, and your ice cream flavor now becomes strawberry. You take another two steps, and the strawberry becomes vanilla. Another three steps, and the vanilla becomes coconut. This is what people call an oscillation. And it can be a function of distance traveled over a function of time. And these only happen if the mass of the particle is not zero."

With the problem of missing solar neutrinos solved, physicists have since moved on to probing how neutrino oscillations work. The big, underlying science question today is whether these flavor changes in neutrinos and antineutrinos happen at the same rate or not, Huber said. If they oscillate differently, that difference—a physical process known as CP violation—could help to explain why our universe consists of us and our surroundings, over light and light alone.

Physicists believe that 14 billion years ago, there were exactly the same amounts of matter and antimatter in the universe. "If that were true, and it always remained like that, then eventually, all matter and antimatter would have met each other and become light," Huber said. "The universe would then contain only light and nothing else. Obviously, that's not how it happened."

Because we exist, it's clear that matter dominated over antimatter during the Big Bang, in a break of symmetry. Neutrino oscillations could show how this was possible by demonstrating their own asymmetry. DUNE provides a way to catch that asymmetry in the act—or not.

The difference in oscillation rate between neutrinos and antineutrinos—or lack thereof—is not going to be glaring, Huber said, which is why physicists like him and Mariani are so fixated on precision. It could come down to tenths or hundredths of a number in DUNE's measurements. Though it's a feat, DUNE is the minimum needed to get it done, Huber said, because in the case of precisely measuring neutrino oscillations, "you need a Saturn rocket to fly to the moon."

"Physics in the last two decades has gone from a field where we're happy just saying, "Oh, we've seen neutrinos, hooray," to the point where we're trying to do very precise measurements," Huber said. "DUNE is the epitome of that. That really is the end of a decades-long evolution where neutrino physics became more and more precise. DUNE is trying to do one of the most precise measurements ever attempted with neutrinos."

A Saturn rocket to fly to the moon

There are some musts in measuring neutrino oscillations: creating enough neutrino events, only a handful of which will be snatched up by an experiment; putting enough distance between the neutrinos' source and their endpoint for them to exhibit their oscillations; and establishing a setup that's massive and highly-resolved enough to capture the energy the events leave behind.

DUNE's answer to this starts with a powerful neutrino beam based at Fermilab in Batavia, Illinois. Here, physicist will shoot neutrinos underground across 1,300 kilometers of underground distance at a 40,000-ton particle detector filled with liquid argon. The detector will be located at the same mining area used by the Homestake Experiment in South Dakota.

As neutrinos bump into the argon inside the detector and leave behind trails of energy, that material will offer unmatched precision in measuring them, Mariani said. "Essentially, it's like taking a photo camera from the 1980s and comparing that with your phone camera that has millions of pixels," he said.

The College of Science has another DUNE connection, quite close, too. Kevin Pitts, who started his tenure as dean of the college this past June and who is an affiliated faculty member of the Department of Physics, last year was named the chief research officer at Fermilab. There, he oversaw the lab's science program, which includes the multibillion-dollar DUNE project.

"The DUNE experiment will be a truly remarkable technological achievement that will lead to truly remarkable scientific insights," Pitts said. "This experiment will feature 40,000 tons of liquid argon a mile underground in an abandoned gold mine in the Black Hills. Scientists from around the world are contributing to this effort because they are excited by the transformational science that will be performed at this facility."

For years, Mariani and Huber have worked at ensuring that this part of the DUNE project doesn't fail. Because scientists don't actually see neutrinos themselves as the particles hit a detector, they must reconstruct the interaction that took place with the energy left behind.

Getting that right depends on the microphysics of what happens within the interaction, Huber said. Reconstructing the interaction is as complex as tracing the effects of shooting a bullet at a clock, he said, "Depending on how you may hit the clock, you may have gears flying out, you may have the numerals fly off. To really reconstruct the clock, or the whole interaction, from that, I need to know the probability for the bullet to eject each given subpart of the system."

When shooting neutrinos at argon atoms, argon nuclei can eject all sorts of particles: neutrons, protons, and new particles like pions, which are easy for detectors to miss and which all need to be counted for an accurate measurement of the total energy produced by the neutrino event. "In our work with Dr. Mariani, I think we were the first group who really tried to look into the details of that and quantify what kind of systematic uncertainties would arise from that," Huber said. "I think that work had a huge impact on how people think about designing the whole experiment."

Huber and Mariani see the Center for Neutrino Physics as one of the few places where that degree of collaboration between theorists and experimentalists could happen. Since its founding in 2010, the center has built up both its theoretical and experimental programs with the sense that as neutrino physics evolved, theorists and experimentalists would always need each other.

When an experimentalist and a theorist go for coffee

In physics, theory and experiments tend to go back and forth in a feedback cycle: the theorists put forward a question, the experimentalists figure out a way to build an experiment to try to answer the question, and once they have the data, the theorists try to figure out what it means.

When theorists and experimentalists have trouble understanding each other, this back and forth won't go smoothly. It's becoming easier and easier for that to happen, Huber said, as carving out a career path in physics tends to push scientists to self-identify as either a theorist or an experimentalist. "By the time you're a grown researcher, you often lose this ability to effectively communicate with each other," Huber said. "I think the only way around this is regular social interaction, where in the end, you learn to understand the language of the other side."

Huber, the center's director, said it's important to look for ways to keep theorists and experimentalists talking, in theory-experiment joint seminars or in something as simple as a shared cup of coffee. "Dr. Mariani happens to have a nice coffee machine," he said. "It's really that you have this casual social interaction and a relationship where nobody feels embarrassed to ask stupid questions. I can go down the hallway and ask any of my experimental colleagues, "Hey, what happens if you did X?" And mostly they will tell me, "Well, X will blow up," or something like that. But sometimes you find you have some genuinely interesting new things you can do."

So it will go with DUNE. The project's ability to surface new insights on neutrinos will depend in part on how its scientists can center their different talents on the same question, Huber said.

DUNE is planned to collect data on neutrino oscillations for 20 years, starting in 2029. It'll be another 10 to 15 years before physicists can find meaning in the results. They may or may not find evidence answering the question of matter's dominance over antimatter in the universe. But DUNE's potential goes beyond that, Huber said.

DUNE represents a facility with technologies physicists will be able to use in ways they haven't yet dreamed up. "This is where it gets really interesting," Huber said. "Once you have this new facility and technical capability, people become very creative and find thousands of other ways to extract new science from that. In reality, what we do in science is driven by curiosity. That's the reason we're doing this."

Provided by Virginia Tech

Citation: Unraveling the neutrino's mysteries at the Deep Underground Neutrino Experiment (2023, January 5) retrieved 26 April 2024 from https://phys.org/news/2023-01-unraveling-neutrino-mysteries-deep-underground.html