Illustration: Sandbox Studio

Bonnie and the ArgoNeuTs

by Kurt Riesselmann

Inspired by heroes of Greek mythology, physicists are on a quest to find a cheaper, more efficient way to capture neutrinos–one of the strangest and most fascinating particles in the universe. Liquid-argon detectors may hold the key to discovering whether neutrinos are the reason that stars, planets, and people exist.

When Bonnie Fleming graduated with a bachelor's degree in physics from Barnard College, a small all-women's college in Manhattan, she wasn't sure she wanted a career in research. She worked as a particle beam operator at a Department of Energy laboratory for three years before deciding to go to graduate school.

"All my bosses were accelerator physicists," she says of her time at Brookhaven National Laboratory. "I decided I wanted to get a PhD and do research, too."

Today, Fleming is a junior faculty member at Yale University and principal investigator of the Argon Neutrino Test project, or ArgoNeuT. With physicists from six institutions, she works on a technology that could be the key to unveiling the role neutrinos played in the early universe.

Neutrinos are one of the most abundant particles in space, and one of the most peculiar. They emerge from nuclear reactions inside stars and from other nuclear processes, such as radioactive decays. Although the Standard Model of particles and their interactions predicts that neutrinos have no mass, experiments have shown, to the surprise of many scientists, that they do have a tiny mass.

Neutrinos come in three types that transform into each other as they travel. Physicists think even more types of neutrinos may exist. Short-lived, ultra-heavy neutrinos may have been present in the early universe, and might have played a crucial role in determining that everything we know today would be made of matter rather than antimatter.

So, are neutrinos the reason we exist?

"It's such a compelling question," Fleming says. "People are made of matter; they can relate to that."

Catching neutrinos

Despite their abundance, neutrinos are hard to detect. They can easily travel all the way through the Earth without interacting with the atoms that make up matter.

"Hold out your hand and count to three," Fleming says with a smile. "A trillion neutrinos just went through your hand."

To increase the likelihood of observing the

Bonnie Fleming leads the Argon Neutrino Test project at Fermilab. To catch neutrinos, scientists place the ArgoNeuT time projection chamber (right) into a vessel (in the back) and fill it with liquid argon. ArgoNeuT will collect tens of thousands of neutrino events within six months. Scientists plan to build a larger detector using this technology.

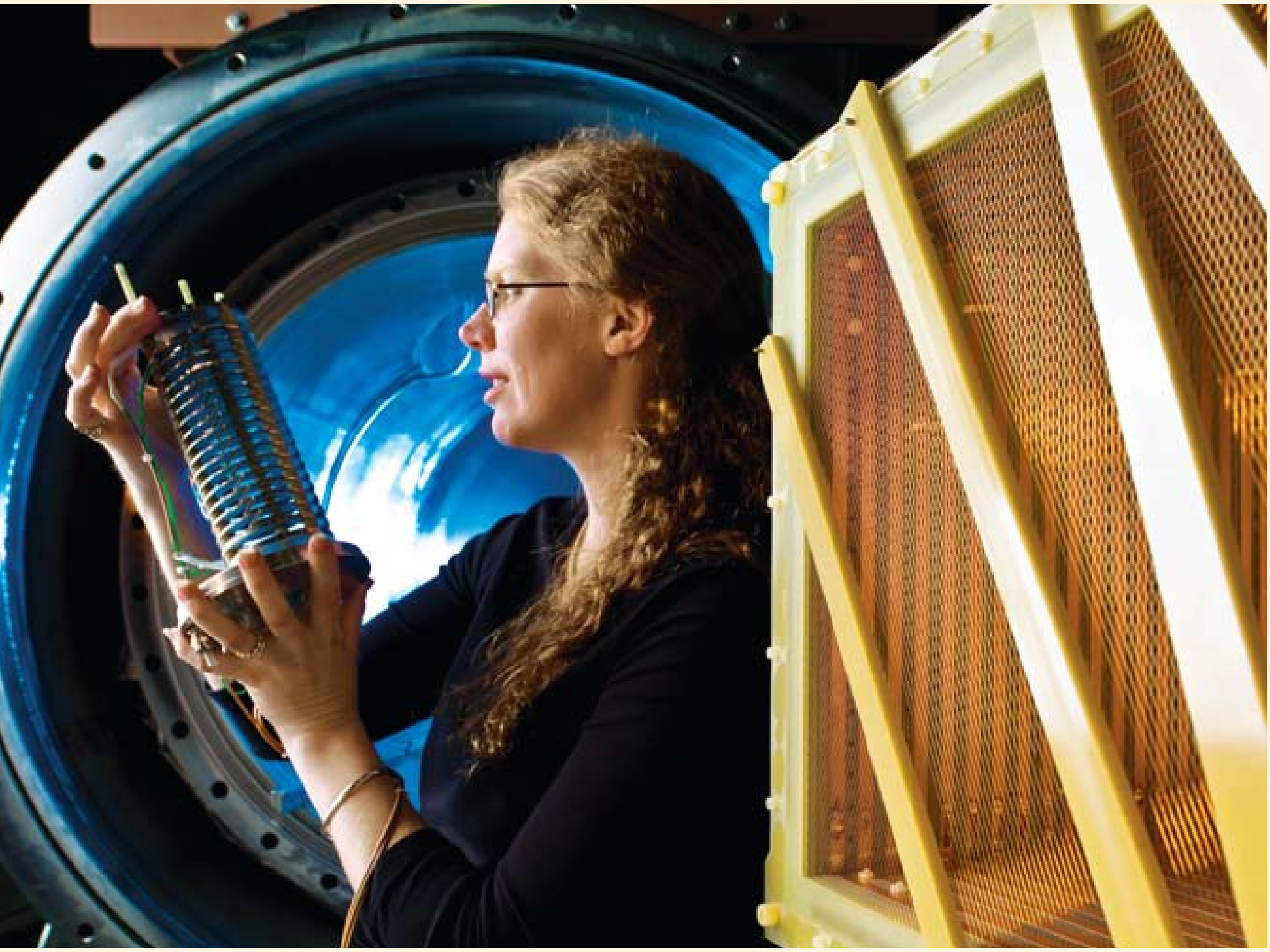


Photo: Reidar Hahn, Fermilab

extremely rare interactions that do occur, physicists build accelerators to generate intense beams of neutrinos, and large, heavy detectors to record the collisions of those neutrinos with atoms. The largest detector to date is the 50-kiloton Super-Kamiokande in Japan, located deep underground in a cylindrical cavern about 40 meters high and 40 meters wide. The cavern is full of water and its walls are covered with light-sensitive devices that register Cherenkov radiation, the faint glow emitted when neutrinos collide with water molecules.

While the interest in even larger neutrino detectors is high, the cost of building these cutting-edge experiments has reached hundreds of millions of dollars. Hence physicists are looking for better, more cost-effective methods. The challenge is to record neutrino interactions at the right energy, in sufficient numbers, and with the most accurate identification of the particles that emerge from the collisions.

"When you embark on a big, expensive project, you'd better evaluate your options carefully," says physicist Regina Rameika, of the Fermi National Accelerator Laboratory near Chicago, who works on ArgoNeuT as well as on plans for much larger neutrino detectors. "We need to find something that is cheap per kiloton."

Liquid-argon neutrino detectors, pioneered by Nobel laureate Carlo Rubbia and his ICARUS collaboration, might be the solution.

Better and cheaper?

Instead of recording light emitted by particles traveling through water, as Super-Kamiokande does, liquid-argon detectors record signals from electrons knocked loose by passing particles.

Rameika thinks a liquid-argon detector could identify three to five times more neutrino collisions than a water Cherenkov detector of the same size. It potentially would better differentiate among the three types of neutrinos, a crucial requirement for the next generation of neutrino experiments.

So far, nobody has built a large, multi-kiloton neutrino detector based on liquid argon, and scientists don't know yet how much this would cost.

The real test for this type of detector will be "to use one to do an important physics experiment. Then you can see what the problems are," Mike Shaevitz of Columbia University says. "The physics community would want to see a physics result before they put money into a large one."

Jason and the Argonauts

The ArgoNeuT project began in 2006 when Fleming secured a National Science Foundation CAREER grant to study the liquid-argon technology. Soon she and her collaborators at Fermilab and other institutions were looking for a catchy name for their project.

"We had a contest," Fleming says. "Rich Schmitt, a cryogenic engineer at Fermilab, came up with the name in a play on Jason and the Argonauts."

According to Greek mythology, the Argonauts were adventurers who sailed across the Mediterranean Sea in their ship, the Argo, to retrieve the Golden Fleece. Led by Jason, the crew braved fire-breathing oxen and sleepless dragons.

Fleming and her ArgoNeuTs face more modern challenges in their quest to develop a small liquid-argon neutrino detector that could eventually be scaled up to the size of a 20-story office building.

Not for time travelers

Argon is a noble, non-toxic gas that constitutes about one percent of air. It exists as a colorless liquid in the narrow temperature range of minus 186 to minus 189 degrees Celsius.

In the early 70s, William Willis and Veljko Radeka, of Brookhaven National Laboratory, built the first detector to use layers of steel immersed in liquid argon to measure the energies of charged particles emerging from collisions. Today, high-energy collider experiments such as the DZero experiment at Fermilab and the ATLAS experiment at the European laboratory CERN rely on similar detectors to record the energies of particle events.

But these sandwich-type detectors, known as liquid-argon calorimeters, cannot reveal the details of a neutrino collision.

"You don't have the picture of the event and you don't know what particle caused the event. You only know the energy," says Flavio Cavanna, professor at the University of L'Aquila in Italy, who works on ICARUS and ArgoNeuT.

Hence neutrino physicists are exploring a type of detector known as the liquid-argon time projection chamber, or TPC.

"My sister loves the name," Fleming says. "It's totally sci-fi for her. She often calls it a time capsule."

Despite its curious name, a time projection chamber has nothing to do with time travel. The term refers to the time it takes for electrons, knocked loose by charged particles, to drift through liquid argon to an array of high-voltage wires that record their arrival time and location. Just as rays of light cast the shadow of a moving object onto a wall, the electrons set free by a moving particle project its trajectory onto the array of wires.

"Many particles come out of a collision, and the TPC traces all the particles and their

Mitch Soderberg works on the ArgoNeut detector at the Proton Assembly Building. *Photo: Reidar Hahn, Fermilab*

interactions," producing images almost like those from a video camera, Cavanna says. Scientists then select the images that are of interest. "You can measure for each track the energy associated with this track, and you can identify the particle that created the track."

Because electrons can drift long distances through liquid argon, a relatively small number of wire arrays, placed a few meters apart, could capture neutrino collisions across a large volume and possibly reduce the cost of a large neutrino detector.

Drifting through an argon sea

Rubbia, spokesperson of the ICARUS collaboration and CERN director general from 1989 to 1993, recognized the potential of large liquid-argon TPCs more than 30 years ago. He hoped to use them to track rare subatomic processes, such as neutrino collisions and elusive proton decays that some theories predict. He has pursued this idea ever since.

"Carlo Rubbia is the father of the long-drift technique for liquid-argon detectors," says Willis, now a professor at Columbia University. "Many people had the idea of building a long-drift detector; Carlo had the strength to do it. He could work on many things at once. He had a number of smart and brave people to work on this."

In 1997, the ICARUS-Milano collaboration recorded neutrino events with a 50-liter liquid-argon detector exposed to a high-energy neutrino beam at CERN. In 2001, the ICARUS collaboration assembled a detector 20 meters long in the INFN-Pavia laboratory and filled one of its two modules with about 300 tons of liquid argon to record cosmic rays, showers of particles created in the Earth's atmosphere.

"We had five months of operation," Cavanna says. "We collected millions of cosmic-ray events. We were satisfied with our physics results, but we were not completely satisfied with the cryogenics system."

After making improvements to the detector, the collaboration moved the two modules underground to Gran Sasso National Laboratory. This fall, ICARUS will begin recording neutrinos from a powerful muon neutrino beam originating at CERN, about 730 kilometers away. The neutrinos travel straight through the Earth—no tunnel needed. The collaboration expects to record about 1300 neutrino interactions with argon per year when the CERN-Gran Sasso beam reaches full strength.

For their part, ArgoNeuT scientists expect to collect tens of thousands of neutrino events within six months.

"The Europeans have solved many problems, in particular in issues related to argon purity and the actual detection of particle tracks," Fleming says. "We owe them a huge amount because of their incredible push to advance this technology over the last 20 years."

Fighting scavengers

In April 2007, a prototype liquid-argon detector, developed at Yale University, recorded its first cosmic-ray tracks. It was the first crucial step in bringing US physicists up to speed with this technology.

"We call it technology transfer," says Fermilab physicist Stephen Pordes.

Pordes works on the US effort to find the best way to fill a time projection chamber with ultrapure liquid argon. If there is too much air in the vessel, it will stop the electrons before they can reach the readout wires.

"The purity of the argon is really the main point of the technology," says Cavanna, who will spend the summer at Fermilab to help with the startup of the ArgoNeuT detector. "Impurities are like scavengers. If the argon is not pure enough, it practically eats the signal that we would detect with our wires."

The level of impurity inside a liquid-argon detector must be less than 50 parts per trillion. ICARUS achieves this by pumping the air out of the detector before filling it. This approach, however, is impractical for detectors that might reach the size of a 20-story building. So Pordes and other physicists are exploring the possibility of pushing the air out of the detector vessel by repeatedly flushing it with argon gas before filling it with liquid argon. Then they further reduce impurities by filtering the liquid argon as it circulates within the chamber.

Next: scaling up

This summer, ArgoNeuT scientists will place their detector into a high-intensity beam of muon neutrinos generated by Fermilab's Main Injector accelerator and begin to take data. They will measure the cross section, or probability, of neutrinos colliding with argon nuclei in the detector. This is an important piece of information for the analysis of data from ICARUS and other, future experiments, Cavanna says.

"We need to know the neutrino-argon cross sections with very high precision," he says. "It is not Nobel Prize physics, but it is important to understand the exposure of a liquid-argon detector to a neutrino beam at low energies. It will show that this technology is suitable for extracting neutrino physics information when implemented in the next generation of experiments."

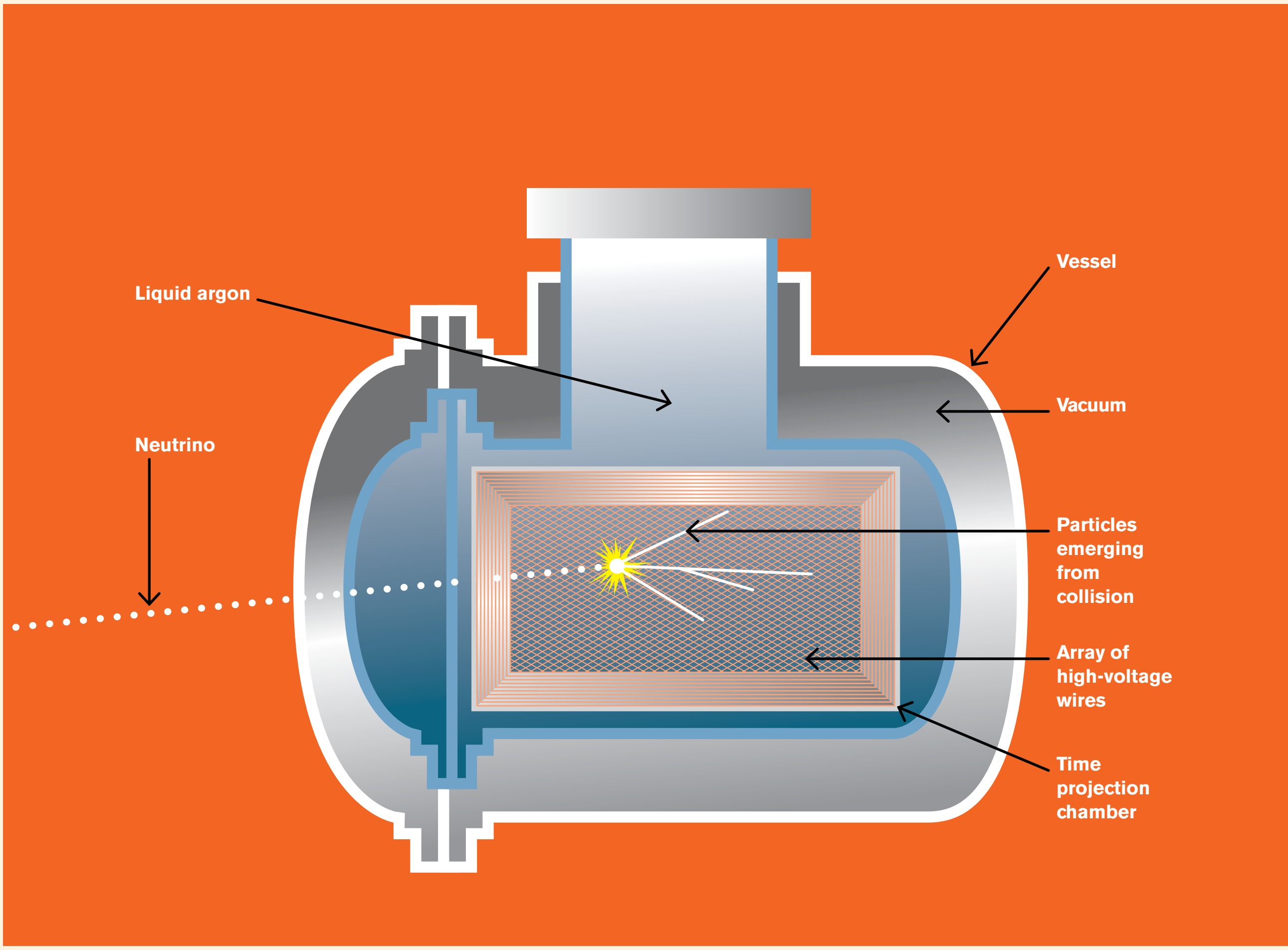
Fleming and other neutrino physicists are already tackling the next step. They plan to build a bigger detector at Fermilab containing 170 tons of liquid argon. It would catch muon neutrinos from a beam generated by the lab's Booster accelerator, and rely on the new method of removing impurities. If approved, the Micro Booster Neutrino Experiment, or MicroBooNE, would be about one-third the size of the ICARUS detector, cost about $6 million in materials and clarify mysterious low-energy neutrino signals seen in an earlier experiment.

"MicroBooNE would be a step beyond ICARUS 600," Fleming says. "If it is built, we would be able to do important physics measurements using a liquid-argon detector that could be scaled to even larger sizes."

Eventually, neutrino physicists hope to build experiments with five kilotons and, ultimately, 100 kilotons of liquid argon to find out whether neutrinos are the reason we and the matter around us exist.

"It's a long haul," Fleming says. "I think the liquid-argon technology will revolutionize the field of neutrino research if we can make it work for very large detectors."

ArgoNeuT records a "video" of the charged particles emerging from the collision between a neutrino or cosmic ray entering the detector and an argon nucleus. The charged particles knock loose electrons, which then travel through the argon to an array of high-voltage wires. The wires record the location and arrival time of the electrons, which reveal the various particle trajectories.



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