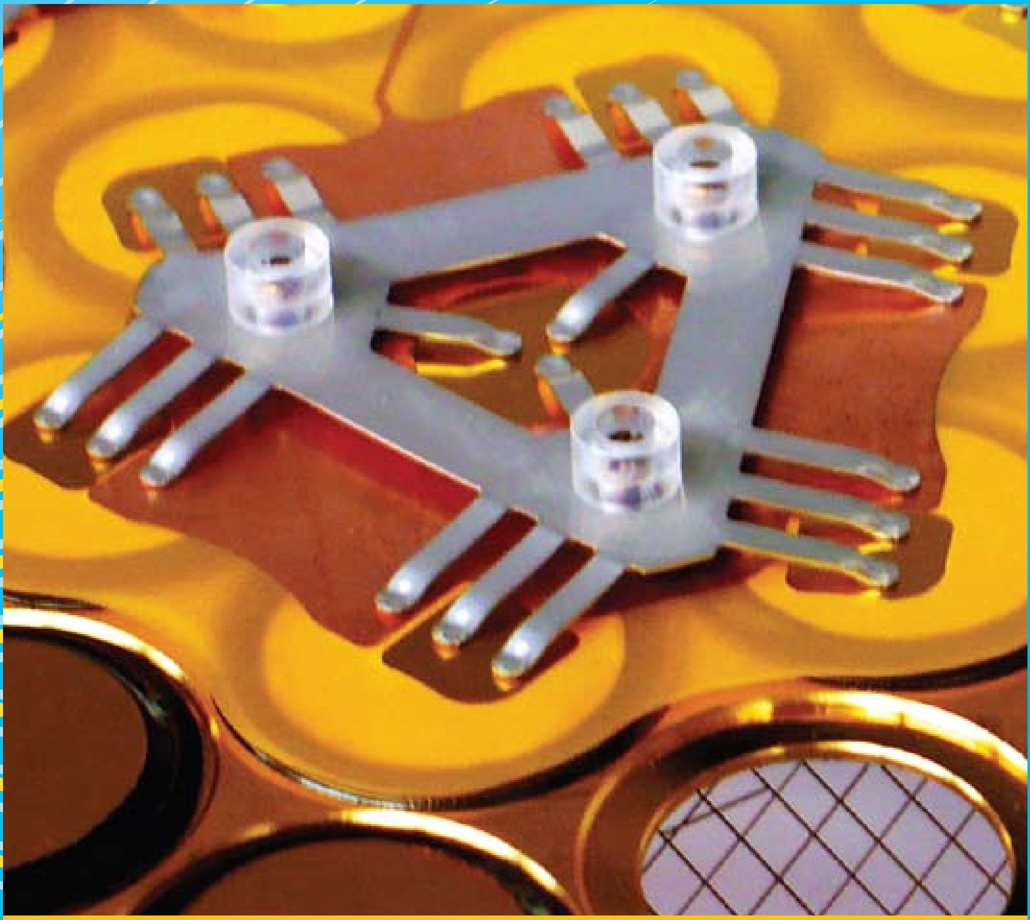
EXO

ENRICHED XENON OBSERVATORY 200

TAKES CLEAN TO AN EXTREME



Photos courtesy of the EXO collaboration

Some particle physics experiments require an extraordinary degree of cleanliness and quiet. How far will they go to achieve this? Try etching tools with acid, setting up shop in a deep salt bed, putting equipment on stilts, and choreographing a 2100-kilometer truck ride so not a moment would be lost.

By Lauren Knoche

This triangular metal gadget is an "APD Spider." It connects EXO's light sensors—the golden circles—with electronics that allow scientists to read out the data from the experiment's detector.

Just before midnight on November 3, 2009, a large truck loaded with 40 tons of cargo pulled away from the Stanford University campus. It carried the last shipment of laboratory equipment from Stanford to New Mexico for a high-energy physics experiment that will begin taking data this year.

Moving complicated experimental equipment is always a delicate process, but in this case the task was more challenging than usual. The experiment, called the Enriched Xenon Observatory 200, or EXO-200, is designed to look for an ultra-rare phenomenon that could reveal key secrets about the nature of the neutrino. This process is so rare that detecting just a few signals over the course of a year would be a triumph. Scientists have no hope of seeing these faint signals unless they eliminate every possible source of background radiation that could get in the way. Yet sources of radiation are everywhere—from cosmic ray particles that rain down from space to materials as common as copper, everyday tools, ordinary rocks, even the human body.

It had taken the 70 scientists and engineers of the EXO collaboration six years to design and assemble their detector—a tank that would hold 200 kilograms of liquid xenon cooled to a very low temperature and heavily shielded by onion-like layers of components. A fanatic degree of cleanliness prevailed at every step. Most of the components were not only assembled in clean rooms, but also shipped in those same clean rooms, shielded and sealed against contamination. Even so, the team choreographed and practiced every move to make sure those containers spent as little time as possible in the open air.

The truck that left Stanford that night was headed for a salt deposit in New Mexico at the US Department of Energy's Waste Isolation Pilot Plant, where the last piece of apparatus would be lowered to its new home 700 meters below ground.

"You go underground because you want to suppress cosmic rays," says EXO spokesperson Giorgio Gratta of Stanford. "Cosmic rays can be energetic enough that they are essentially unstoppable with reasonable amounts of matter, so you need lots of matter to filter them out. Whether it's a salt mine is not essential, but you generally need about one kilometer of ground above."

Cleanliness starts from scratch

Ensuring that there is no residual radioactivity in the detector began with material selection. EXO designers ordered candidate materials from "clean" manufacturers—companies aiming to create products free of radioactivity—and screened all of them to make certain that every piece of material incorporated in the experiment was "clean."

Samples were inserted into a nuclear reactor to expose them to radioactivity, then tested to see how they responded, says Jesse Wodin, a postdoctoral researcher working on EXO-200 from Stanford and SLAC National Accelerator Laboratory. Any material exposed to radioactivity will become slightly radioactive itself, but some retain this property longer than others; "We chose the cleanest material we could."

After finding the best materials, including ultra-pure copper, Teflon, and lead, construction began in clean rooms at Stanford's End Station III. These were not just the usual clean rooms intended to prevent contamination by dust and other particulate matter. They also needed to prevent contact or proximity with anything that has low-level radioactivity, which means most everyday materials. The facility sports a five-foot-thick concrete roof that helps to block harmful background radiation. Here the EXO team tackled challenges in maintaining cleanliness during construction of the project.

Given the need to use only carefully selected non-radioactive materials, "solder might as well be pure uranium,"

says Stanford and SLAC graduate student Nicole Ackerman. So rather than soldering components together, the designers used springs made from special screws and bent washers. These "clean" springs were used for every connection in the detector, which is called the time projection chamber, or TPC.

Each tool used in construction of the EXO-200 experiment had to be submerged in acetone and alcohol and sonicated, a process that uses high-frequency sound waves to disrupt any impurities on the surface of the tool. The tools were then rinsed with water and dried before double-bagging for transport to the clean room where they would be used. The outer bag, having seen a "dirty" environment in transport, was removed in a transition room so that only the inner bag and tool entered the clean room.

If the tool was to come in direct contact with the TPC, an additional precaution was taken, called acid etching. In this technique, the tool was immersed in a strong acid that effectively removed the outer layer of molecules from the tool. Because the acid could harm the ultra-pure materials, acid etching was followed by multiple washes in distilled water and ethanol.

An extra-speedy truck trip

As construction finished, plans for shipping the EXO-200 components were finalized. Cosmic rays are more intense at airplanes' flight altitudes than at ground level. While not harmful to humans at this level, they would do irreparable damage to the experiment's components by causing some atoms to become radioactive. That meant the experiment could not be taken by plane; every piece of equipment had to be driven by truck to New Mexico. It took five separate trips in 2007 and 2008, as well as the final shipment of the detector in November 2009, to bring the entire experiment to WIPP.

Cleanliness was the top priority every step of the way, from extracting each container from the Stanford lab to loading it onto the truck, unloading it at WIPP, and lowering it into the mine. Each shipment was planned and carried out with extreme precision and caution, but the team took extra precautions with the detector.

"Certain portions needed to be transferred as fast as possible," Wodin says. "If atmospheric radiation hits copper, it can make a little impurity that undergoes radioactive decay two years later. The TPC was placed in a 60,000-pound concrete vault and the entire container was closed up at Stanford to go to WIPP." In addition, the TPC set off on its 30-hour trek at 11 p.m. so it would arrive in the morning of the second day, giving the team a full span of daylight to safely maneuver the detector underground and not leave it above ground any longer than necessary.

Two drivers took turns at the wheel so the truck would not have to stop for rest breaks; those extra hours would have left the TPC vulnerable to harmful amounts of cosmic ray exposure. With such delicate equipment on the 18-wheeler, the organizers also worried about vibrations and acceleration forces.

"We used an air-ride truck," Gratta says. "We also installed accelerometers so that we could check what kind of accelerations or vibrations our load was subject to."

The TPC is made of both metal and plastic components, which shrink and expand at different rates when temperatures change. This could easily damage the detector by placing tension on wires and connections. So the team waited until fall, when temperatures are more moderate, to ship the detector, and took other precautions as well. "We painted the container with special reflecting paint to help keep it cool," Ackerman says.

Snuggling into the salty depths

The truck drivers took the detector more than 2100 kilometers before rolling into the WIPP site, a storage facility for nuclear waste maintained by the US Department of Energy. Crews quickly unloaded each container from the truck and put it on a rail car that glided into the cage of a waste conveyance—an elevator intended for lowering nuclear waste into the mine. Its large size helped efficiently lower the loads delivered for the EXO-200 project, but space was tight. The EXO team built each container to fit the dimensions of the elevator with about one centimeter to spare.

The detector and its surrounding layers weighed 40 tons, the heaviest load that the conveyance can lower. The innermost layer is a copper drum that would be filled with 200 kilograms of pure liquid xenon. The drum is surrounded by HFE fluid, which acts like antifreeze to keep the xenon at the ideal temperature of minus 103 degrees Celsius. A copper can holds the fluid, and the can is encased in 25 centimeters of lead.

The lead protects the experiment from background radiation emitted by the ground in which the machine is buried. Additionally, salt has naturally lower background radiation than many of the Earth's other common materials. Common low-energy emission elements—such as uranium and thorium—that occur in hard rock were filtered out in the geochemical process that formed the salt bed, leaving the site with a lower concentration of these elements. "Roughly speaking, the salt is about 1000 times less contaminated with uranium and thorium than a hard-rock mine," Gratta says. "But shielding more of this radiation would not have been a big deal. If we were in a regular mine less clean than WIPP, we could have used roughly 40 centimeters of lead." The salt environment's natural protection means the physicists don't need to use as much lead shielding as they would in some other underground location.

Seeking a rare, revolutionary decay

Shielded from background radiation, researchers hope to detect a theorized phenomenon called neutrinoless double beta decay by the footprints it leaves in the tank of liquid xenon.

In normal double beta decay, two neutrons become protons, ejecting two electrons and two antineutrinos in the process. Neutrinoless double beta decay is theorized to be very similar, except that no antineutrinos would be emitted. But in order for this to happen, the neutrino would have to be its own antiparticle. It would be the first particle with mass that is known to have this property.

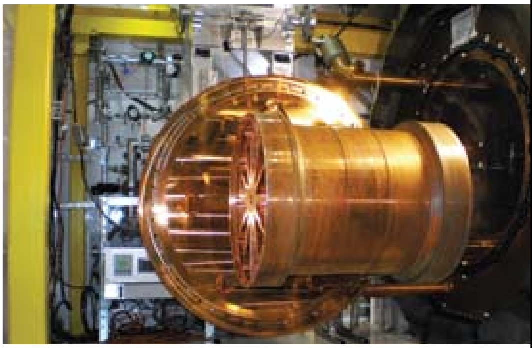
Finding this rare decay would be a revolutionary discovery about the fundamental components that make up the universe.

"Discovering that there are particles that have this funny property is a big deal," Gratta says. "Part of the interest is that we would be discovering a new way for particles to behave, and that's very important."

A second draw for studying the neutrino is to better identify its mass. Researchers know the neutrino has a mass of less than two electronvolts, making it at least 250,000 times lighter than the electron. But thus far, physicists have been unable to pinpoint a more accurate mass. The Standard Model of particle physics, a theoretical framework that allows scientists to calculate many interactions, does not predict masses of particles and was built around the idea that neutrinos are massless like photons, the particles of light.

"There is no theory that ties together masses and then explains, for example, why an electron is lighter than a proton," Gratta says. "Neutrinos are very strange because they are incredibly light, so it is possible that understanding a little bit more about how neutrino masses come about will allow us to understand masses in general and how particle masses are produced."

But catching a neutrinoless double beta decay is no easy task. "These events are as rare as they make them," Gratta says. "It's possible that it is so rare that it doesn't



exist. This is slightly funny, but it's the right answer because the rarer the decay is, the smaller the neutrino mass. So if this thing is infinitely rare, the neutrino mass is infinitely small."

Salt air, bunny suits, and clean rooms on stilts

The WIPP site employees were nervous about the tight squeeze down the elevator, and had practiced every maneuver with a large dummy box before containers began arriving. Planning and practicing paid off. Each container fit, allowing the cage door to close and the containers to be lowered 700 meters into the salt deposit.

This is no stereotypical rattling-and-shaking mine shaft elevator; it was designed for lowering delicate cargo. "The conveyance is actually very smooth and excruciatingly slow on the scale of mines," Gratta says.

The EXO-200 underground experiment area is like a long highway tunnel, apart from the copious amounts of salt and dust, Gratta says. The experiment's zone is far from the nuclear waste site.

"People may wonder how come we want to do this low-radioactivity experiment in this place where they have all this radioactive waste," Gratta says. "But the radioactive waste is a kilometer away, and of course this shields it plenty. In fact, we've got lots of help to go there because the facility is happy we are living proof that their storage facility is not a problem."

At Stanford, the team had built one large clean room with dividers. As shipping began, the area was sectioned into six smaller clean rooms. These were closed up individually, encasing their contents, and transferred one at a time to WIPP. Once underground, the rooms were reassembled with one difference—they were put on stilts.

"The advantage of being in salt is that it has lower radioactivity than hard rock," says Gratta. "The bad thing about salt is that it moves." Because salt is incredibly soft, it will slowly creep under pressure, like that provided by the weight of six clean rooms and an 80-ton cryostat surrounded by lead shielding. "That means the floor comes up, so we have our clean rooms sitting on stilts with hydraulics and every few months we re-level them," Gratta says, appearing undaunted by the idea that the salt is constantly shifting around the $15 million experiment. "Eventually this thing will collapse, but eventually means more than 20 years and we will hopefully be done by then."

High amounts of salt in the air at WIPP also pose a threat to the EXO experiment. To keep salt dust from entering the experiment rooms, the air is thoroughly filtered and scientists must enter the experimental chamber through a number of airlocks.

Only six clean rooms were needed to house and ship the EXO experiment, but two additional clean rooms were used to ship extra materials and tools. These two rooms were kept underground and serve as transition rooms for scientists entering or leaving the experiment. As physicists enter the mine, they don coveralls over their clothes. In transition rooms, the scientists remove the salty coveralls, wash their hands and faces, and change into bunny suits before entering the experiment.

The TPC is now installed, and tests are under way to prepare the experiment to start up in mid-2010, Wodin says.

After years of preparation, the EXO team's hard work to protect their experiment from ever-present background radiation is about to be put to the test.