Searching for the Neutrino's Identity

by Matthew Early Wright

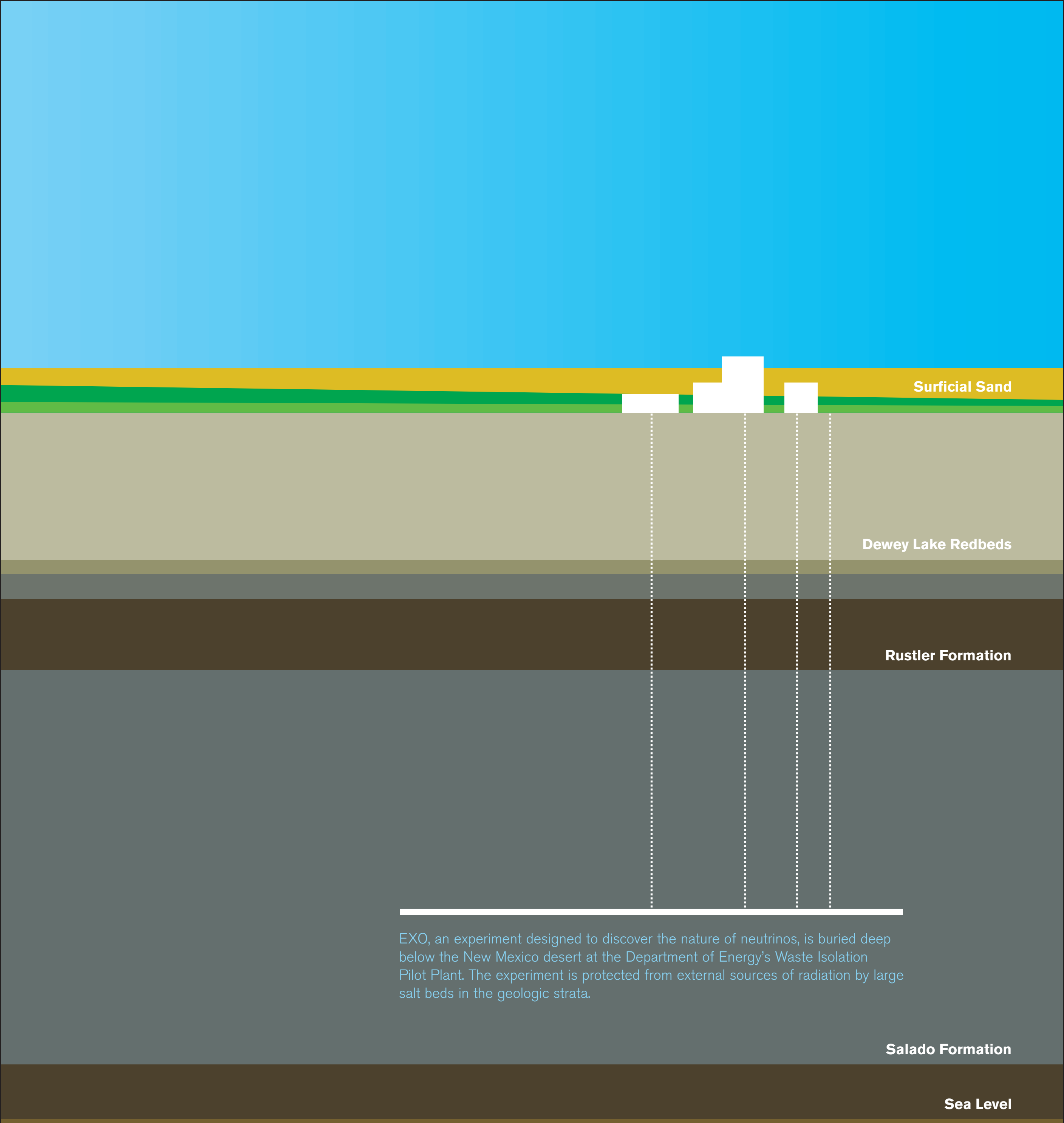
Neutrinos are like no other particle in the universe. The more we learn about these "little neutral ones," the less we seem to understand them. Physicists do not even yet know what type of particle the neutrino is. But experiments looking for a rare decay process might soon provide the answer.

Neutrinos should have no mass and come in three unchanging "flavors". At least that's how the Standard Model, physicists' most complete description of fundamental particles, tells it. But recent experiments have revealed that neutrinos do not play by these rules: they have mass and the flavors morph into one another as they travel through space.

As a result, more questions tug at the minds of neutrino researchers than ever before: What are the exact masses of the neutrinos? Is it possible that neutrinos are their own antiparticles? Do neutrinos really oscillate between flavors? Do they break the standard matter-antimatter symmetry?

Several experiments seek answers to the first two questions by searching for a rare type of nuclear decay called neutrinoless double beta decay. Theorists suspect these decays occur, and a Heidelberg-Moscow experimental group has claimed evidence for them based on a controversial analysis. But so far no experiment has been able to unambiguously document neutrinoless double beta decay.

Because of immense interest in the topic, a range of new experiments, prototype detectors, and experiment proposals are under consideration. Some of these include the Enriched Xenon Observatory (EXO), the Cryogenic Underground Observatory for Rare Events (CUORE), the Molybdenum Observatory of Neutrinos (MOON), and the Majorana experiment.



EXO, an experiment designed to discover the nature of neutrinos, is buried deep below the New Mexico desert at the Department of Energy's Waste Isolation Pilot Plant. The experiment is protected from external sources of radiation by large salt beds in the geologic strata.

"Observing this type of decay would be a Class I discovery, the highest goal achievable," says Stanford University physicist and EXO project leader Giorgio Gratta. "It would be an important step toward understanding nature in general."

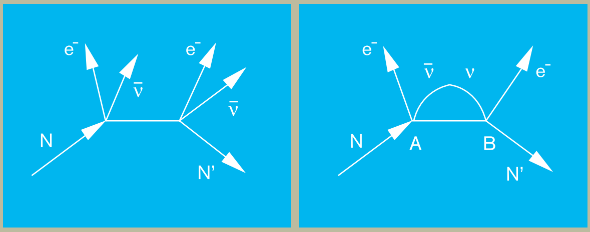
The physics community at large agrees with Gratta. In a 60-page report, *The Neutrino Matrix,* published in November 2004, members of the American Physical Society (APS) Multi-Divisional Study on the Physics of Neutrinos outlined the most compelling areas of study. The report placed a high priority on experiments to observe neutrinoless double beta decay, stating that it "is the only practical way to discover if neutrinos are…a new form of matter."

Gratta and his collaborators from Stanford University, Stanford Linear Accelerator Center (SLAC), and eight other institutions believe EXO is a nearly ideal tool to see these elusive decays. According to the APS report, combining the results of experiments similar to EXO offers the best strategy to answer many of the perplexing questions surrounding the neutrino.

Of particles and antiparticles

Theorist Paul A. M. Dirac predicted that every type of fermion should have an antimatter partner of equal mass but opposite electric charge. These particles with distinct antimatter counterparts now carry his name. Neutrinos, which conspicuously lack a charge, do not obviously nor necessarily fit this pattern in the same way as quarks and other Dirac particles.

Assuming that neutrinos and antineutrinos are distinct particles, experiments have seen both of them where expected: antineutrinos in decays that also produce electrons, and neutrinos in decays that also produce positrons.



Left: Standard double beta decay. As the nucleus (*N*) decays into a new nucleus (*N'*), two neutrons convert to protons, releasing two electrons (e^-) and two antineutrinos ($\bar{\nu}$). The decay energy is split between the electrons and antineutrinos. Right: Neutrinoless double beta decay. If neutrinos and antineutrinos are Majorana, an antineutrino can be emitted from the first neutron (*A*), then absorbed as a neutrino by the second (*B*). Only the two electrons will be released, carrying all the decay energy.

However, the lack of charge allows for the possibility that an antineutrino is the same particle as the neutrino. Italian theorist Ettore Majorana proposed this idea, and the phenomenon of a particle being identical to its antiparticle is named after him.

The discovery of neutrino mass has pushed the issue to center stage. In order to reconcile massive neutrinos with the Standard Model, theorists must first know whether neutrinos are Dirac or Majorana in nature.

The easiest approach to this problem is to look for neutrinoless double beta decay. A form of nuclear decay that occurs rarely at best, it can only happen if neutrinos are Majorana in nature. But as Gratta says, "even if neutrinos are massive and Majorana, we might not see double beta decay happen too often. It's a lot like looking for a needle in a haystack."

Standard double beta decay, in which two antineutrinos are released from the decaying nucleus, has already been observed. In this process, two neutrons convert to protons, releasing two electrons in addition to the two antineutrinos. Experiments can detect the electrons while the antineutrinos escape without leaving a trace.

Neutrinoless decay is a different matter. Single beta decay can occur with either the emission of an antineutrino or the absorption of a neutrino. If neutrinos are Majorana, an antineutrino is the same as a neutrino. Hence the antineutrino emitted in one beta decay can be absorbed as a neutrino by the second one, resulting in neutrinoless double beta decay (see figure).

In this case, only two electrons will be released, and they carry as much energy as the four particles emitted in standard double beta decay. As a result, the two electrons emitted in the neutrinoless decay have slightly more energy than the two electrons in the standard decay.

"The only experimentally measurable difference between two-neutrino decay and zero-neutrino decay is the energy of those electrons," says EXO project scientist Martin Breidenbach of SLAC. "We must measure this energy difference with good resolution. There's no other way."

If EXO observes neutrinoless double beta decay, physicists will have a strong case to argue that neutrinos are their own antiparticles. And they'll be well on their way to answering a second key question: what are the neutrinos' masses?

Weighing the unweighable

"There are experiments that limit how large the neutrino mass is," says EXO project scientist Charles Prescott, also at SLAC. But below this point, it's anyone's guess what the actual mass is. "It's open territory. EXO is a true experiment. We don't know what to expect."

Results from past experiments suggest the neutrinos' masses are tiny. At such small mass scales, scientists prefer to express mass in units of energy. The upper limit on neutrino mass that Prescott refers to is around one electronvolt (1 eV). This number is supported by accelerator experiments, data on supernovae, and other lines of evidence, he says.

Neutrino oscillation experiments have made some progress toward understanding the differences in mass between pairs of neutrinos. However, absolute mass values remain elusive. For example, the lightest neutrino could have a mass almost anywhere between exactly zero and the 1 eV ceiling.

Experiments like EXO can explore mass ranges below 1 eV, either by discovering the absolute mass scale if neutrinoless double beta decay is observed, or by pushing the upper limit of neutrino masses lower and lower if it isn't. The key to success is the relationship between the rate of neutrinoless decay and neutrino mass: If neutrinos are heavier, decays should be seen more often. Turning this around, rarer decays mean lighter neutrinos.

EXO will look for neutrinoless double beta decay in heavy liquid xenon, starting with a relatively small, 200 kg detector capable of seeing decays if they occur at a high rate. This prototype detector, now in development, will be sensitive to masses as low as 100 meV (millielectronvolt). "But if we see nothing, it doesn't mean nothing is happening," Gratta explains. "It might be that we need to build a larger detector."

If the prototype fails to find neutrinoless decays within three to five years, a larger, one to ten ton detector can be used to probe down to 20 meV or lower. And if, after continued efforts, no neutrinoless double beta decay is seen, physicists will have to consider that neutrinos might not be Majorana, but Dirac, particles. In that case, theories that attempt to explain the extremely light mass of the neutrinos based on their Majorana nature will need to be abandoned.

The search is on

The EXO prototype, due to begin operation in late 2005, will use "enriched" xenon, consisting of 90 percent of the relatively rare isotope xenon-136, the only xenon isotope that could undergo neutrinoless decay.

Xenon offers advantages over other nuclei such as germanium and tellurium, which are being used in other experiments. It is a noble gas, and therefore easy enough to purify and enrich, as long as suitable facilities are accessible. To obtain enough enriched xenon for the prototype, the EXO collaboration relied on colleagues at the University of Moscow.

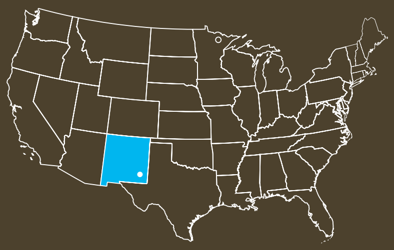
"The infrastructure in the US is optimized for uranium separation," Gratta explains. "The Russian infrastructure is more generic and lends itself well to separating xenon."

If neutrinoless double beta decay occurs in the EXO tank, it will cause a faint flash of light and leave behind an ion of barium-136. Both can be used as evidence that a decay has occurred. However, the prototype will detect only the flash of light; the challenge of identifying barium will be left for a future upgrade. The EXO team has already made significant progress toward engineering a system to pluck the occasional single barium atom from a large tank of xenon.

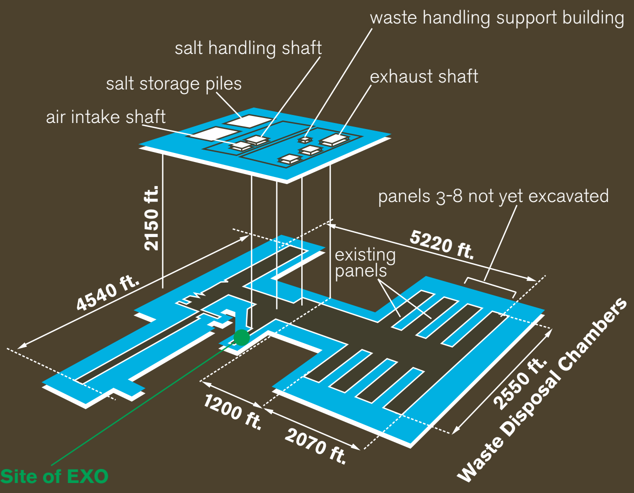
The EXO team has another hurdle to jump. Any neutrino observatory must be buried deep underground to avoid false signals from bombardment by cosmic rays. But going deep isn't enough, since metals and minerals in the surrounding rock can also contain radiologically active materials. For this reason, physicists look for subterranean areas where radiological interference is low.

The EXO prototype will be installed deep beneath the New Mexico desert at the Department of Energy's Waste Isolation Pilot Plant (WIPP). It may seem strange to install an experiment that hopes to escape radiation in a large nuclear waste repository. But the salt walls of the facility provide shielding from all sorts of radiation, including the waste in the adjoining chambers. In fact, according to Breidenbach, "WIPP is one of the more radiologically quiet places on Earth, as long as we're upwind of the plutonium."

But since EXO's threshold of sensitivity is so incredibly low, the team has to protect itself from a seemingly unlikely source: background interference can also come from the detector itself.



The DOE's WIPP nuclear waste repository near Carlsbad, NM. The EXO prototype will begin operation here in late 2005.



Schematic of the WIPP underground site, more than 600 meters underground. EXO will be separated from the waste disposal chambers by a wall of salt over 300 meters thick.

"The shielding and the materials surrounding the detector have to be very pure, and free of radiological contaminants like uranium, thorium, and potassium," Prescott says.

Gratta likes to use a tangible example: "The chair you're sitting on is very radioactive on the scale that we care about."

Despite such challenges, Gratta, Breidenbach, Prescott, and their collaborators are confident that EXO will work and is worth the effort.

The neutrino is shaking the Standard Model to its foundations. Yet the secret identity of this mysterious little particle might help to lay the first bricks in a new edifice of particle physics.