GEOPHYSICS

Mapping the Earth's Engine

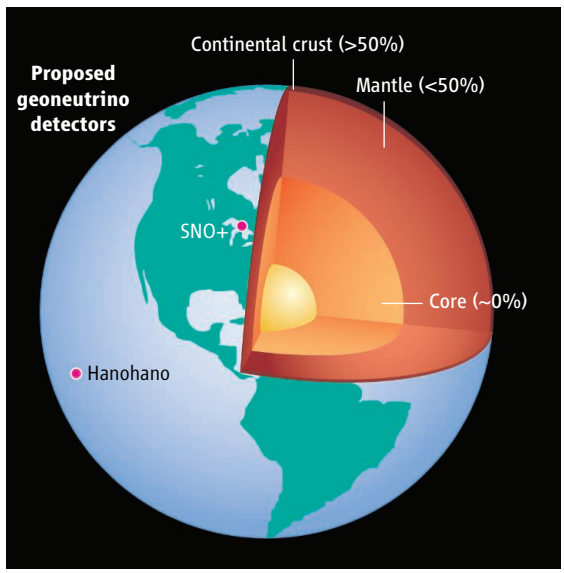
Neutrinos created by nuclear decay may allow geoscientists to measure the distribution of radioactive elements in the Earth.

William F. McDonough

Particle physicists and geophysicists rarely meet to compare notes, but earlier this year researchers from these two disciplines gathered to discuss antineutrinos (the antiparticle of the neutrino) (*1*). These fundamental particles are a by-product of reactions occurring in nuclear reactors and pass easily through Earth, but they are also generated deep inside Earth by the natural radioactive decay of uranium, thorium, and potassium (in which case they are called geoneutrinos). Particle physicists have recently shown that it is possible to detect geoneutrinos and thus establish limits on the amount of radioactive energy produced in the interior of our planet (*2*). This year's joint meeting was aimed at enhancing communication between the two disciplines in order to better constrain the distribution of Earth's radioactive elements.

Researchers from the Kamioka Liquid scintillator Anti-Neutrino Detector (KamLAND) in Japan reported results that are consistent with the power output produced from the decay of thorium and uranium (16 TW), and the abundances of these elements in Earth, as estimated by geoscientists (*3*). (Potassium geoneutrinos cannot be detected at present due to the high background in this region of the spectrum.) The initial measurement is also broadly consistent with the Th/U ratio for Earth being equal to that of chondritic meteorites, which is a fundamental assumption used by geochemists to model planetary compositions. However, the upper power limit determined by the experiment (60 TW at the 3σ limit) exceeds Earth's surface heat flow by a factor of 1.5 and is thus not very useful as a constraint for the models.

Nevertheless, there is great excitement within the two communities, as advances in antineutrino detection are anticipated. The KamLAND detector was intentionally sited near nuclear reactors in order to characterize antineutrino oscillation parameters (the reactor produces so-called electron antineutrinos, and antineutrinos can oscillate between the three different "flavors"—the electron, muon, and tau antineutrinos)—and sense fluctuations in reactor power output. Consequently, the reactor signal overwhelmed the geoneutrino signal. New detectors are being developed, deployed, and positioned in locations that have substantially smaller contributions from nuclear reactors, and thus will provide more precise measurements of neutrinos and antineutrinos to both the Earth science and astrophysical communities.



Inside story. One model of the distribution of radioactive elements potassium, thorium, and uranium in Earth. New antineutrino detectors in Canada (SNO+) and Hawaii (HANOHANO) should allow more precise determination of these distributions.

In addition to detecting geoneutrinos, these facilities are designed to detect neutrinos from supernovae and determine their oscillation properties (like antineutrinos, neutrinos can oscillate among their three different states). As particle physicists continue to count geoneutrinos, the signal-to-noise ratio will improve and, with more counts, the uncertainty in the radioactive energy budget of Earth will shrink and the measured Th/U ratio of the planet will be determined to a greater precision. Measurement uncertainties of 10% or better are possible with the new detectors, and are achievable with only 4 years of counting.

What does this mean for the Earth sciences? Geoneutrino detectors will be sited on continental crust of different ages, including ancient cratons, the oldest pieces of continents (see the figure). One proposal is to convert the Sudbury Neutrino Observatory (SNO) to "SNO+" (*4*). This 1000-ton detector is sited in a mine in Ontario, Canada, and represents an optimal location for measuring the distribution of heat-producing elements in the ancient core of a continent. Here, the antineutrino signal will be dominated by the crustal component at about the 80% level. This experiment will provide data on the bulk composition of the continents and place limits on competing models of the continental crust's composition. The Boron Solar Neutrino experiment (Borexino) detector, situated in central Italy (and hence somewhat removed from the regions of France with many reactors), has begun counting (*5*). This detector will accumulate a geoneutrino signal from a younger continental region and surrounding Mediterranean ocean basin, thus receiving a greater proportion of its signal from the mantle.

Particle physicists from Hawaii and their colleagues from elsewhere in the United States, Japan, and Europe are proposing a 10,000-ton, portable geoneutrino detector that is deployable on the sea floor. This detector, called Hawaii Antineutrino Observatory (HANOHANO, which is also Hawaiian for "magnificent"), would allow the measurement of the geoneutrino signal coming almost exclusively from deep within Earth, far removed from the continents and nuclear reactors (*6*). Thanks to the capability of multiple deployments, this detector would provide the exciting possibility of obtaining signals from different positions on the globe.

Ultimately, these different detectors will allow Earth scientists to test various models for the vertical and lateral distribution of thorium and uranium in Earth and will yield unparalleled constraints on the composition of the continents and the deeper Earth. Insights from geoneutrinos will also allow us to decide among competing models of Earth's interior. Decades of research on the state of mantle convection have assumed wide-ranging values of the Urey ratio, the proportion of radioactive energy output to the total energy output of the planet. Geochemists have deduced a Urey ratio of ~0.4, whereas geophysicists prefer constructing mantle convection models assuming higher Urey ratios that

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Published by AAAS

range up to 1.0 (*7*). In addition, geoneutrino data, coupled with local heat-flow data, will be used to evaluate models of bulk continental crustal composition. Competing models differ by almost a factor of 2 in their concentrations of potassium, thorium, and uranium, with some models critically dependent on heat-flow data (*8*).

Beyond determining the amount and distribution of heat-producing elements in Earth, particle physicists at the workshop described future experiments, only a decade or so away from implementation, that would allow more precise determination of Earth's structure. Dispersion of neutrino beams penetrating Earth are a function of the electron density of different layers of the planet. The Earth's core, composed of high-density metal, has a markedly higher electron density than the silicate shells of Earth. Likewise, there is a marked contrast in electron density for the inner and outer core. Measurement of neutrino dispersion in these layers would substantially improve our knowledge of the absolute radius of the core and hence the precision of global seismological models. Such beam studies could also place limits on the amount of hydrogen in the core.

The range of novel experiments underway and those just over the horizon will directly interrogate the interior of Earth in exciting and unparalleled ways (*9*); these tools will essentially provide new ways of "journeying" to the center of the Earth.

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10.1126/science.1144405

ENGINEERING

Privacy By Design

George Duncan

New technologies are being developed to protect the privacy of individuals in today's information society.

Information privacy used to come by default, mainly because of the high costs imposed on any snooper. Yet today, technology has lowered the costs of gathering information about individuals, linking personal details, storing the information, and broadcasting the results. Inexpensive networked surveillance cameras capture our digital image across time and place. Terabyte RAID (redundant array of independent disks) drives provide cheap storage. Real-time data integration software turns fragmented personal data into composite pictures of individuals (*1*). Communication that is universal, instantaneous, unlimited in capacity, and free for all (*2*) is becoming ever more plausible.

With cost barriers lowered for data capture, storage, integration, and dissemination, our privacy is no longer implicitly protected (*3*). Instead, those charged with protecting information privacy must now give it explicit attention. This is the purpose of two thought-provoking reports released this year (*4*, *5*).

In its report, the U.S. National Research Council recommends that fair information practices be adopted by businesses in the use of personal information and that mechanisms be developed to give individuals more control over the use of their information (*4*). Perhaps the most controversial recommendations involve increased privacy regulation: the establishment of a Federal Privacy Commissioner or Privacy Commission, greater federal regulation of businesses that use personal information, and more government action to protect individual information privacy.

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The report from the U.K. Royal Academy of Engineering emphasizes that, because of human rights law, organizations maintaining systems that use personal information should be accountable for designing them to provide privacy (*5*). The report recommends less intrusive data use (such as preferring client authentication—"are they valid users?"—over identification—"who are they?"), research on how camera surveillance can ignore law-abiding activities, developing clarity about privacy expectations, formation of trusted third-party organizations as guardians of personal data, and making data collection and use transparent to the data subject. It advocates strengthening the powers of the U.K. Information Commissioner to include substantial penalties for misuse of data.

There are many important reasons to use personal information. For example, under Megan's Law, Web sites permit the public to locate and identify convicted sex offenders in the United States. Depersonalized data on patient drug use can be mined to better target marketing efforts for pharmaceuticals; this approach is used, for example, by Verispan (*6*). Web-based social networks like Jaiku or Twitter facilitate peer-to-peer exchange of personal details. Road tolls can be debited electronically from a driver's personal account while monitoring every vehicle's speed and recording safety violations.

But in the wrong hands, this personal information can be used to exploit or harm individuals; for example, released sex offenders may be subject to harassment, employers may discriminate against those with certain medical conditions, children on social networks may be targeted by those with evil intent, and car owners may be held accountable for what thieves may do with their cars.

To help balance privacy concerns and the need for personal data, a new paradigm is emerging, in which system designers conduct privacy risk assessments and incorporate privacy as a fundamental design parameter. As Alan Greenspan has remarked (*7*), "The most effective means to counter technology's erosion of privacy is technology itself." To illustrate how privacy-enhancing technologies

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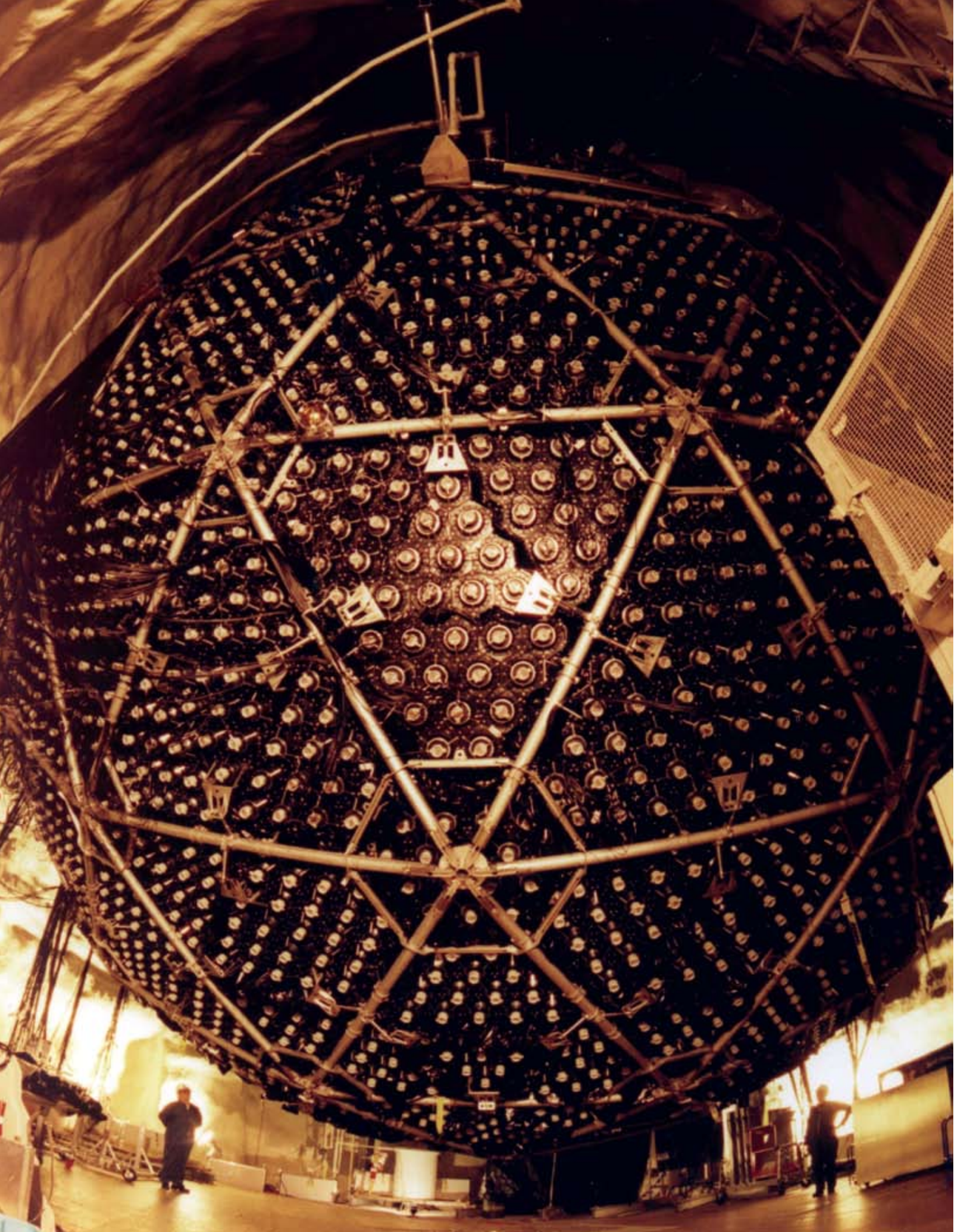
Published by AAAS



COURTESY OF LAWRENCE BERKELEY NATIONAL LABORATORY

Originally used to detect elusive particles from space called neutrinos, the four-story detector at the Sudbury Neutrino Observatory could be retrofitted to detect antineutrinos produced by natural radioactivity inside Earth.

For a big view of inner Earth, catch a few ...

geoneutrinos

By Diana Steele

Were the Earth a crystal ball, you might gaze 2,900 kilometers down to its outer core with a telescope. The Earth, though, is frustratingly opaque — to light. Most knowledge of the planet's internal structure comes from studying seismic waves, which give a kind of ultrasound image. Inferences about Earth's internal chemistry rely on the elements found in near-surface rocks, meteorites and the sun.

Recently, geoscientists have developed a new tool for probing the Earth's innards. Borrowing a page from astrophysics, they are using the curious subatomic particles known as neutrinos. Astrophysicists have used neutrino telescopes for decades to study neutrinos originating in the sun and elsewhere in the cosmos. Now earth scientists are taking a neutrino telescope and looking down, to illuminate the Earth's interior by detecting "geoneutrinos" — neutrinos produced within the planet itself.

"Now, for the first time, we have the possibility of measuring the composition of the Earth in real time," says William McDonough, a geochemist at the University of Maryland in College Park.

Geoneutrinos are actually antineutrinos, which are neutrinos' antimatter counterpart, just as positrons are the antimatter partner to electrons. "'Geoneutrinos' is just an easier word to say than 'antineutrinos coming from inside the Earth,'" McDonough says. Electrons and positrons have opposite electrical charges, but neutrinos and antineutrinos have no charge. So neutrinos and antineutrinos, confusingly, may or may not be the same particle.

Geoneutrinos were first observed in a detector deep inside a mine in Japan in 2005. Now an array of proposed new experiments are poised to get an even better glimpse of the Earth's inner chemistry. These range from deep-mine detectors in Canada, the United States and Europe, to a mobile, submersible deep-ocean detector.

McDonough and two colleagues from the University of Hawaii gave an overview of the experiments in October in *Eos*, the weekly newspaper of the American Geophysical Union, and earth scientists discussed new developments with particle physicists at a conference in September in Sudbury, Canada — the site of one of the proposed experiments.

Geoneutrinos originate from the radioactive decay of uranium, thorium and potassium in the Earth's crust and mantle. Earth scientists are keen to learn more about the crucial role the decay of these elements may play in heating up the Earth and, in turn, driving convection in the Earth's mantle.

Powering Earth

"The convection in the mantle is responsible for essentially all of the dynamics of geology that we see — moving continents and seafloor spreading," says John Learned, a particle physicist at the University of Hawaii at Manoa. But whether radioactive decay dominates the heating action or is one of a number of players isn't known. There's even controversy over how much heat, in terms of power, the Earth puts out; estimates range from 30 billion to 44 billion kilowatts.

Energy drives the movement of the geologic plates upon which the continents ride, says McDonough, "and the fuel for that is either entirely radioactive fuel or a subset of energy sources." It's like the energy mix in homes, he says. "We don't get all of our electricity from coal, but some portion from nuclear and some portion from other sources. The question today is, 'What are the energy sources driving the Earth's engine?'"

Among the other possible energy sources is heat left over from the planet's formation by colliding meteorites. These planetary building blocks eventually accreted enough mass to become Earth. As the meteorites slammed into each other, their kinetic energy became thermal energy. Over time, the Earth has radiated this heat into space.

"We could have started out with a large amount of kinetic energy, and we've slowly dissipated it," says McDonough, "or we could have started with a large amount of kinetic energy and rapidly dissipated it, depending on the atmospheric conditions."

It's difficult to measure how much heat might have come from this or other sources. But the new suite of geoneutrino detectors could pin down better numbers for the radioactive contribution.

Estimates are that radioactivity, mainly from uranium and thorium but also from potassium, accounts for at least 40 to 60 percent of Earth's interior heat. These elements are probably most abundant in the crust, the top 30 kilometers or so of rock. But key to understanding Earth's dynamics is knowing the amount of these elements in the mantle — the vast, viscous, slowly churning layer that stretches 2,900 kilometers from crust to the molten outer core.

Like the better-known solar neutrinos, geoneutrinos can pass through thousands of miles of solid rock without being stopped or even deflected. That makes them ideal for studying deep Earth — but also makes them very difficult to catch.

Catching geoneutrinos

One surefire way to catch some is to build a detector near a concentrated source of antineutrinos. Conveniently, the uranium and other radioactive elements used in a nuclear reactor provide a flood of these ghostly particles.

That's why the first geoneutrino detector was built near a cluster of reactors in Japan, with an aim to further characterize antineutrinos. Consequently, particles from the reactors swamped those produced by naturally occurring uranium in the crust and mantle.

Nonetheless, in 2005, this experiment, called KamLAND (short for Kamioka Liquid Scintillator Anti-Neutrino Detector), provided the first glimpse of geoneutrinos and a first approximation of uranium and thorium's contribution to the Earth's heat. Unfortunately, because the number of geoneutrinos was so small, the estimated heat contribution, in terms of power, had a range of 19 billion to 60 billion kilowatts; consistent with but not more precise than previous estimates.

Since then, the geoneutrino detector Borexino, located in an Italian mine, has come online. And new experiments are on the horizon, though it may be at least two years before the first of the next generation of detectors starts up.

The SNO+, or Sudbury Neutrino Observatory Plus, would sit two kilometers underground in the Creighton nickel mine near Sudbury, Ontario. SNO+ would piggyback on and use the same detector as a highly successful solar neutrino project called the Sudbury Neutrino Observatory, which played an important role in solving a long-standing conundrum. Researchers had detected fewer neutrinos coming from the sun than expected. SNO showed that neutrinos have a tiny bit of mass and are shape-shifters, turning from a detectable form into another, undetectable one.

Converting SNO into SNO+ — which would detect the lower-energy geoneutrinos — means changing out the fluid that filled the detector. SNO operated from 1999 to 2006 using heavy water — water with atoms of deuterium, heavy hydrogen — to snag solar neutrinos. Pending final approval of funding, the detector will be filled with a hydrocarbon-based scintillation fluid, which, when a geoneutrino is caught, will luminesce and trigger the detector.

The fluid is a common, mass-produced petrochemical called linear alkylbenzene, or LAB, used to make clear detergents, like liquid hand soap. It's less toxic than most chemical liquid scintillators.

"It produces a lot of light, and it's very transparent, but it's a safer scintillator," says SNO+ director Mark Chen. "It's much easier to use it, especially in a setting where we are taking a thousand tons of it into an active mine."

The detector is a four-story acrylic sphere surrounded by electronic eyes that scan the fluid for flashes of light characteristic of geoneutrinos' presence.

Chen, a particle astrophysicist at Queens University in Kingston, Canada, hopes SNO+ will start up in late 2010. It should catch about 50 geoneutrinos a year, considerably more than either KamLAND or Borexino. The longer SNO+ runs, the better the picture it will get of the inner Earth.

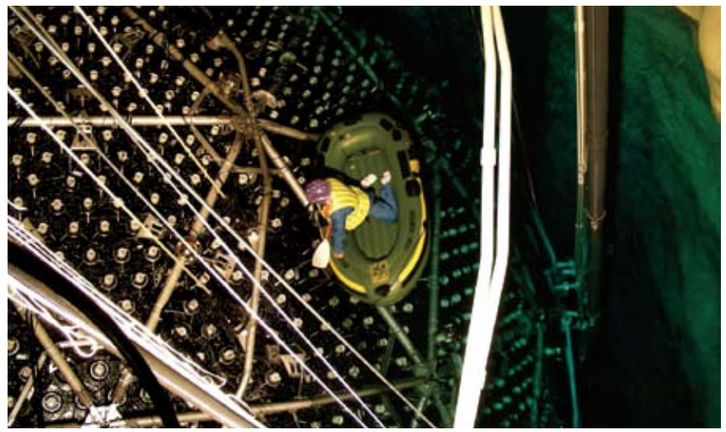
Ontario's nuclear power plants are far enough away to not overwhelm the geoneutrino signal. "Certain problematic backgrounds from cosmic rays are even further reduced because we just happen to be deeper underground than other, similar detectors," Chen says. With SNO+, he says, it will be possible to do some interesting things "with less background and improved precision."

SNO+ has an ambitious scientific agenda that includes better understanding the fundamental nature of neutrinos. One goal is to pin down the mass of the neutrino — a quantity even more elusive than the neutrino itself. Another is to determine whether neutrinos and antineutrinos are the same particle — the lack of charge makes it difficult to tell.

That question "connects to our understanding of the early universe and might inform us about why ... we see matter in the universe but much less antimatter," Chen says.

Mantle signature

SNO+ is the furthest along of the up-and-coming geoneutrino experiments. Other detectors under discussion include one in the Homestake mine in South Dakota and a large detector to be built in Europe, possibly in Finland. Startup and operating costs are estimated to be on the order of hundreds of millions of dollars, and construction wouldn't begin for at least several years.



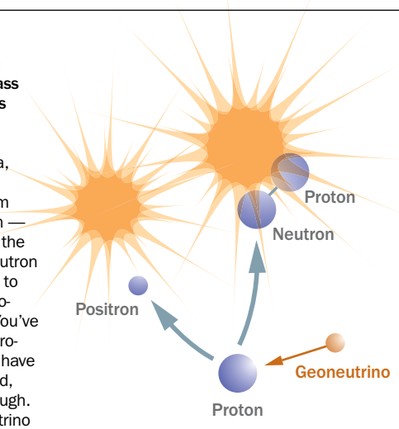
A physicist boats in water surrounding Canada's SNO detector, which is filled with heavy water to detect neutrinos. A new fluid will be used to detect geoneutrinos.

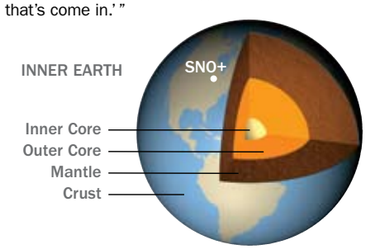
LEFT PAGE: SNO+ COLLABORATION; TOP: GRAPHIC BY J. KORENBLAT; DETECTOR PHOTO COURTESY OF BERKELEY LAB; EARTH IMAGE FROM ISTOCKPHOTO/ALESVELUSCEK

They came from Earth

Like its cousin the neutrino, a geoneutrino (an antineutrino produced in Earth) can pass through Earth unimpeded and, researchers hope, into detectors built to catch it.

At the proposed SNO+ detector in Canada, passing geoneutrinos would collide with protons in fluid inside the detector (bottom right). Such a collision gives off a positron — producing a flash of light — and changes the proton into a neutron (right). When the neutron approaches another proton, the two bond to create deuterium (a heavy version of hydrogen), producing a second flash of light. "You've got a flash associated with the positron production, and 200 microseconds later you have another flash," says University of Maryland, College Park geochemist William McDonough. "And you say, 'Eureka! I've got an antineutrino that's come in.' "





These detectors would be, for the most part, counting geoneutrinos that originate in the Earth's crust, where thorium and uranium are concentrated. Looking close to the crust is like having your eye close to a bright flashlight.

To get a better idea of what's going on in the mantle — a dim and more distant flashlight — requires a geoneutrino detector situated in a place where the crust is only a few kilometers thick, like at the bottom of the ocean.

McDonough and his colleagues are proposing a 10,000-ton submersible detector they have named "Hanohano" (Hawaiian for "magnificent"), for the Hawaii Anti-Neutrino Observatory.

Hanohano would be about 10 times the size of the SNO+ detector and filled with the same scintillator fluid. It would be towed out to sea on a barge and sunk, anchored about 4,000 meters deep and about 90 m from the bottom. After catching neutrinos for a year or two, it could be serviced and redeployed elsewhere. Like SNO+, Hanohano will be a multifaceted experiment, with research agendas in astrophysics and particle physics as well as earth science.

With funding, Hanohano could be built within about two years, McDonough estimates. Preliminary design studies for Hanohano are underway, and McDonough is hoping for another $5 million of seed money to continue design. But to construct and deploy Hanohano and to keep it running for 10 years could cost around $200 million, he estimates.

That's expensive, but it's about a factor of 10 less expensive than sending a spacecraft to another planet, points out David Stevenson, a planetary physicist at the California Institute of Technology in Pasadena, who is not directly involved in the geoneutrino experiments. And "it's inconceivable to me that we could get the same information with the accuracy we desire by any other method," he says.

He also hopes for the unexpected. "I've learned as a planetary scientist, that when you go to a planet, you actually discover things, you are surprised," he says. "And in the case of the neutrinos, you may be surprised. You may be surprised, for example, to discover that there's a major source of radioactivity in a layer just above the core" — an idea proposed early last year by Dutch and South African scientists writing in the *South African Journal of Science*.

Another scenario, which Stevenson thinks is extremely unlikely but Learned acknowledges "would be quite cool," is that enough uranium exists in the core that there is essentially a nuclear reactor humming away down there.

San Diego–based independent scientist J. Marvin Herndon first proposed such a core reactor in 1993. Although not widely believed, his hypothesis would explain some puzzling observations, such as an excess of an isotope of helium emitted from volcanoes, Learned points out.

Hanohano would be able to tell fairly quickly whether such a reactor exists at all, Learned reported last May at a neutrino symposium in New Zealand.

For all their promise, these geoneutrino detectors won't be able to unearth the whole picture of Earth's interior.

Stevenson points out that all the geoneutrino detectors proposed share a shortcoming: They can't detect the geoneutrinos coming from radioactive potassium-40. These geoneutrinos have too little energy to trigger the detector.

"So there is one part of the expected heat production that we cannot measure, and haven't figured out how to measure," he says. And although only a tiny fraction of potassium-40 is actually radioactive, and most of it has already decayed over Earth's 4.6-billion-year history, potassium still contribute up to 20 percent of the radioactive heat, Stevenson says.

"But if you go back in time, potassium-40 becomes increasingly important," he adds. "And that's why, if you want to reconstruct the history of the Earth, you would like to know how much potassium you had." ■

Diana Steele is a freelance science writer based in Ohio.

Explore more

- Visit the SNO+ website at snoplus.phy.queensu.ca/