Geologically produced antineutrinos provide a new window into the Earth's interior

July 29 2005

In Jules Verne's nineteenth century classic Journey to the Centre of the Earth, an Edinburgh professor and colleagues follow an explorer's trail down an extinct volcano to the Earth's core. Ah, fantasy! Here's reality: For more than a century after Verne wrote his novel, geophysicists have had only one tool with which to peer into our planet's heart—seismology, or analysis of vibrations produced by earthquakes and sensed by thousands of instrument stations worldwide. But now, geophysicists have a new tool for studying the Earth's interior, reported in the July 28 issue of the journal Nature

That tool is a gift from unlikely collaborators—physicists who study neutrinos, subatomic particles that stars spew out, and their antiparticles, called antineutrinos, which emanate from nuclear reactors and from the Earth's interior when uranium and thorium isotopes undergo a cascade of heat-generating radioactive decay processes. A detector in Japan called KamLAND (for Kamioka liquid scintillator antineutrino detector) has sensed the geologically produced antineutrinos, known as "geoneutrinos." This new window on the world that geoneutrinos open could yield important geophysical information, according to the Nature paper's 87 authors from more than a dozen institutions and four nations.

"There are still lots of theories about what's really inside the Earth and so it's still very much an open issue," said Giorgio Gratta, a Stanford physics professor who with Stuart Freedman, a nuclear physicist with a joint appointment at the Lawrence Berkeley National Laboratory and the University of California-Berkeley, is co-spokesman for the U.S. part of the collaboration. "The neutrinos are a second tool, so we're doubling the number of tools suddenly that we have, going from using only seismic waves to the point where we're doing essentially simple-minded chemical analysis."

Said Freedman: "This is a significant scientific result. We have established that KamLAND can serve as a unique and valuable tool for the study of geoneutrinos with wide-ranging implications for physical and geochemical models of the Earth."

Added physics Professor Atsuto Suzuki, director of the Research Center for Neutrino Science, vice president of Tohoku University and a spokesman for the KamLAND experiment, "We now have a diagnostic tool for the Earth's interior in our hands. For the first time we can say that neutrinos have a practical interest in other fields of science."

The Japanese Ministry of Education, Culture, Sports, Science and Technology; the Japan Society for the Promotion of Science; and the U.S. Department of Energy funded the experiment.

Receiving their doctorates as a result of work reported in the paper were two of the authors—Nikolai Tolich, a former Stanford doctoral candidate who is now a postdoctoral fellow at the Lawrence Berkeley National Laboratory, and Sanshiro Enomoto of Tohoku University.

In the dark to see the light

"How well do we know our planet?" Gratta asked. "We have very few diagnostics. We only know essentially the crust of our planet. We can measure mountains. We can sample rocks on the surface of the Earth. We can drill holes a few kilometers deep and sample stuff down there, but in terms of chemical analysis or what kind of rocks there are, beyond a few kilometers, you simply don't have access."

What scientists can learn from seismology is limited. Seismic waves travel through the planet as either compressional waves, which pulse like sound and can travel through anything, or shear waves, which wobble side-to-side like shaken jelly but cannot propagate in liquids, which cannot store the energy needed to generate side-to-side motions. These waves travel at different speeds and refract differently when they traverse the interfaces between different types of rocks. So seismology gives information about the locations of boundaries of different types of rock, Gratta said.

Geoneutrinos, in contrast, provide crude information about chemistry. "Essentially [geoneutrinos reveal] just the chemistry of how much uranium and how much thorium is there," Gratta said. "You don't know anything about the crystal structure, whether the thorium is thorium oxide or thorium nitride. But still, when you know nothing, knowing a little bit already makes a big difference. This is really the first tool to actually do this."

Scientists originally built KamLAND in 1997 to reproduce in the lab, using antineutrinos from nuclear reactors, what they saw in nature with solar neutrinos—the phenomenon that the three "flavors" of neutrinos/antineutrinos "oscillated," or turned into the other flavors, as they propagated through space. They saw the same thing in both cases. Previously neutrinos were thought to lack mass, but the oscillations told them that neutrinos must have a very tiny mass—less than 500,000 times less than that of an electron, Gratta said.

"That was a big deal because there's lots of neutrinos in the universe, and the mass of the universe is to some extent influenced by the mass of those neutrinos," Gratta said.

Unlike the energetic sun, which is a gigantic generator of neutrinos, the Earth emits only a modest number of antineutrinos—and scientists need a huge detector to be able to see them. KamLAND was built with the size and sensitivity required to detect Earth-made antineutrinos. In a cavern underneath a Japanese mountain shielding the experiment from the background noise of cosmic radiation, KamLAND consists of about 2,000 photomultiplier tubes, each 20 inches (51 centimeters) in diameter and contained in a 59-foot (18-meter) vessel, bathed in 1,000 tons of liquid scintillator.

"Scintillator is essentially a mix of baby oil—lots of it—and benzene," Gratta explained. "To this cocktail you add a little bit of fluorescent material. When particles interact with this cocktail, they make a little flash of light that then is recorded by light sensors. These are the photomultiplier tubes."

The detector sees when particles arrive and measures their energies. Nuclear reactors produce antineutrinos quickly—the detector sees about one a day. The Earth is not so prolific—the detector sees about one a month. Antineutrinos from nuclear reactors have a different energy spectrum than those from the Earth's interior, so scientists can tell them apart. Thorium and uranium also have different energy spectra, so scientists can tell the geoneutrinos made from each apart, too.

Future possibilities

What's next? Bigger detectors are on many scientists' wish lists. A larger detector would allow scientists to spot an event every few days instead of one a month. Ideally, the detector would be far from nuclear reactors in a location with well-characterized surface geology. Some scientists have considered placing large detectors in mines in Australia, South Africa, Canada and South Dakota. Others favor underwater detectors near island systems such as Hawaii. "The ocean water would shield cosmic radiation, and the very thin oceanic crust would contribute little to the neutrino signal, giving the best sensitivity to neutrinos from deep inside the planet," Gratta explained.

Norman Sleep, a Stanford geophysics professor, thinks geoneutrinos will bring his field revolution, not evolution. Radioactive heat drives plate tectonics, he said, and getting accurate ratios of thorium to uranium isotopes will help scientists better understand deep-Earth processes. The KamLAND results, while of limited statistical power, show a number of neutrinos consistent with what's expected from existing models, the Nature authors wrote. "Now we'll be able to resolve the Earth as a sphere," Sleep said.

"It's a revolution," Gratta agreed, "but let me temper this a little bit with the physicists' point of view—that is, those are very difficult measurements and those detectors are very expensive and large. So before the revolution really comes to fruition, I think it'll take some time, I would imagine one or two decades, before we have more of those detectors and maybe larger ones built in the appropriate place for geophysics."

Researchers from the following KamLAND collaborating institutions also participated in the study: University of Alabama, California Institute of Technology, Drexel University, University of Hawaii-Manoa, Kansas State University, Louisiana State University, University of New Mexico, University of Tennessee, Duke University, University of North Carolina-Chapel Hill, North Carolina State University, Beijing Institute of High Energy Physics, University Bordeaux I and CNRS (France).

Source: Stanford University

antineutrinos-window-earth-interior.html