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# Exploring Earth's Composition and Energetics With Geoneutrinos

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The production of heat by radioactive decay plays a major role in the evolution of the Earth. Present constraints of the amount of heat production come from conflicting assessments of global surface heat flow, which can be directly measured. A high value of  $44 \pm 1$  terawatts accounts for significant heat flow through the ocean floor by both conduction and hydrothermal convection [Stein, 1995]. A low value of  $31 \pm 1$  terawatts assumes only a minor hydrothermal effect [Hofmeister and Criss, 2005]. This heat flux is thought to result from heat production and cooling of the planet.

The relative size of these contributions and their origin allow a range of models. Models are often compared via the ratio of radioactive heat generation to heat flow, called the Urey ratio. Estimates of the Urey ratio, based on chemical models of the early Earth, range from 0.4 to 0.8 [Kellogg *et al.*, 1999; Korenaga, 2003], reflecting the cooling of the planet and indicating the time for heat conduction to the surface. Different models have significantly different implications for Earth's composition, formation, and evolution. Thus, resolving the question of how much heat is produced by radioactive decay within the Earth will refine the models that help describe the Earth.

A new technology has emerged that provides the first direct constraints on poorly known concentrations of radioactive elements in the Earth and the heat they generate. This involves measuring the flux of geoneutrinos, which are produced within the Earth along with heat by the decay of radioactive isotopes of uranium, thorium, and potassium. Neutrinos come from nuclear beta decay in the Earth, but they also can be produced by similar processes in the Sun and nuclear reactors.

The Earth is glowing with neutrinos. Millions of these uncharged elementary particles flow out of every fingernail-sized area of Earth's surface every second. However, because they interact with other particles only via the weak force, almost all neutrinos pass unaffected through the Earth, making them difficult to detect.

Nevertheless, detecting neutrinos is crucial for understanding the planet's geological history. The concentrations of radioactive elements, which reflect the process by which Earth accreted 4.6 billion years ago,

are one of the most important controls on the planet's subsequent thermal, chemical, and mechanical evolution. As a result, they are crucial to understanding processes such as mantle convection, plate tectonics, and the core's dynamics and magnetic field.

## Neutrino Detection

Detecting geoneutrinos employs essentially the same technology used five decades ago to discover neutrinos from a nuclear reactor: a large vat of clear liquid viewed by inward-looking photomultiplier tubes. Mineral oil, a relatively inexpensive, clear liquid containing a significant fraction of hydrogen and whose free proton nucleus is a good neutrino target, is usually used within the vat. Scintillating material, which emits visible light proportional to the energy of ionizing particles created in a neutrino interaction, is dissolved in the oil. The scintillation light is collected by photomultipliers and used to identify neutrino interactions by reconstructing their energy and position.

The challenge of detecting geoneutrinos comes from their tiny probability of interacting. Unless neutrino flux is extremely high, as it is close to a nuclear reactor, only an enormous detector can observe a reasonable interaction rate. The KamLAND detector, located in a kilometer-deep zinc mine on the Japanese island of Honshu and which was built for measuring reactor neutrinos, weighs 1000 tons and records about one geoneutrino per month.

This small detection rate makes reduction of background noise, which is due primarily to cosmic rays and radioactivity in and around the detector itself, a primary experimental concern. The Earth attenuates cosmic rays, so geoneutrino detectors operate best in tunnels, mines, or the deep ocean. Deeper is better, with an overburden equivalent to several kilometers of water usually considered a minimum. Size, radio-purity of materials, and shielding make detecting geoneutrinos a major project.

Although geoneutrinos and reactor neutrinos both are produced in the decay of neutron-rich nuclei, they can be distinguished by their energy spectra. In this form of beta decay, a radioactive isotope emits an electron and an antineutrino when one of its neutrons spontaneously changes to a proton (Figure 1). Geoneutrinos and reactor neutrinos are thus antineutrinos, the antiparticles

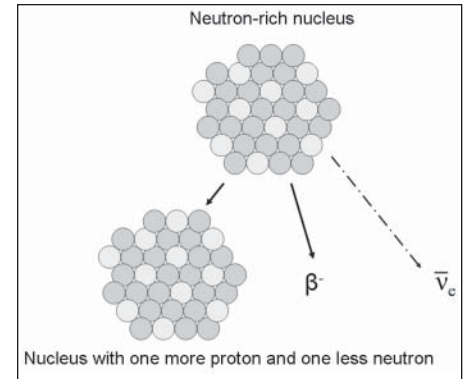


Fig. 1. The beta-decay radioactive process in which a neutron decays into a proton, emitting an electron (beta-minus particle) and an antineutrino, and releasing heat.

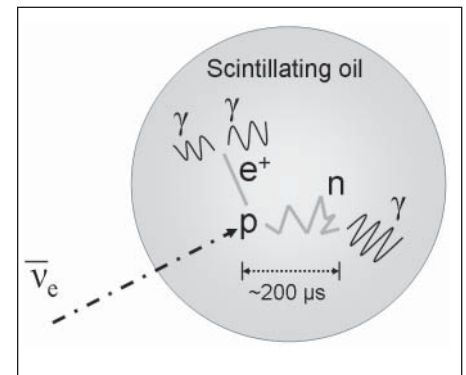


Fig. 2. Antineutrinos ( $\bar{\nu}_e$ ) are detected by inverse beta decay, which causes a characteristic sequence of events.

of neutrinos. The energy available to the antineutrino, derived from the daughter nucleus being more tightly bound than the unstable parent, is shared in varying amounts with the electron. Sometimes the electron gets no energy, defining a cutoff to the antineutrino spectrum characteristic of the particular transformation. If the daughter nucleus itself is unstable, transformation continues until a stable daughter is produced. Because reactor neutrinos and geoneutrinos come from different radioactive isotopes, they have different energy spectra.

Antineutrino detection relies on inverse beta decay, the reverse of the reaction that produced the antineutrinos. Antineutrinos with enough energy initiate a distinct signature upon colliding with a proton. In the collision, the proton converts to a neutron while the antineutrino becomes a positron (Figure 2). Both products interact quickly in ordinary matter, producing ionizing particles. The positron annihilates with an atomic electron, and later the slowed neutron is captured by a nearby hydrogen nucleus, forming deuterium. The positron's ionization signal is proportional

to the antineutrino energy, providing information about the radioactive source, and the neutron's signal corresponds to the binding energy of deuterium. These two signals, closely separated in time and space, form a distinctive coincidence that distinguishes antineutrino detections from background.

Geoneutrino measurements reflect the concentrations in the Earth of radioactive isotopes with decay times comparable to the Earth's age. Because shorter-lived isotopes are no longer present, only uranium, thorium, and potassium continue to provide significant internal heating. Radioactive isotopes of uranium and thorium undergo a series of alpha and beta decays leading to stable isotopes of lead. Radioactive potassium decays directly to calcium. The geoneutrino energy spectrum is punctuated by cutoffs determined by the excess binding energy of the daughter nuclei.

Only the highest-energy geoneutrinos from the decay series of uranium and thorium initiate inverse beta decay, whereas geoneutrinos from potassium do not have enough energy. Because potassium has a different chemical behavior from uranium and thorium, it may have a much different distribution within the Earth. In particular, it may be the light element in the core [Gessman and Wood, 2002; Rama Murthy *et al.*, 2003], in which case radioactive heat would be produced there as well as in the mantle and crust. The consequences of radioactivity in the core make the development of techniques for detecting potassium geoneutrinos a high priority.

Detecting geoneutrinos at several locations provides insight into spatial variations of radioactivity. The geoneutrino flux at all locations has a baseline component from the mantle, and a contribution originating mainly from crust within several hundred kilometers of the detector. Continental crust is thicker and has a higher concentration of radioactivity than oceanic crust. Compared with the geoneutrino flux from the mantle, the flux from continental crust should be several times greater, whereas the flux from the oceanic crust should be several times less.

Although the mantle is predicted to have the lowest concentration of radioactivity, its enormous volume results in a measurable geoneutrino flux. Thus, a detector in the middle of the ocean should effectively measure the radioactive content of the mantle and core. In contrast, a detector in the middle of a continent effectively measures the radioactive content of the surrounding crust. Because the oceanic flux is lower than the continental, a seafloor detector needs to be larger than a terrestrial detector to observe geoneutrinos at the same rate. Continental and oceanic detectors would provide a complete estimate of Earth's geoneutrino flux and constrain its radioactive abundance.

#### Observational Program

Measuring and interpreting geoneutrino flux is the goal of several major experimental

Table 1. Comparison of Characteristics of and Annual Event Rates for Geoneutrino Projects <sup>a</sup>				
Location	KamLAND Japan	Borexino Italy	SNO+ Canada	Hanohano Hawaii
Crust	continental	continental	continental	oceanic
Current status or start date	operating	2007	2008	planning
Depth (meters water equivalent)	2700	3700	6000	4500
Target ( $10^{32}$ free protons)	0.35	0.18	0.57	8.7
Geoneutrinos per year, total	13	8	30	110
Geoneutrinos per year, mantle	4	2	5	81
Reactor neutrinos per year	89	6	32	12

<sup>a</sup>Reactor neutrino rates assume all reactors running at full power.

projects, summarized in Table 1, which are drawing considerable interest among an emerging community of physicists and geophysicists. The initial KamLAND measurement announced last year [Araki *et al.*, 2005; McDonough, 2005] demonstrates the potential of geoneutrinos for investigations of Earth's internal heat sources. A subsequent workshop in December 2005 in Hawaii, which reported present and planned instrumentation and explored the future use of geoneutrino data, reflected interest in ensuring that the program grows. A session at the 2006 AGU Joint Assembly in Baltimore, Md., provided a venue for further development of the program. In addition to presenting plans for geoneutrino measurements of radioactivity from throughout the Earth, the session explored how these measurements can help resolve crucial issues such as the role of hydrothermal heat transfer and the possible presence of radioactive heat sources in the core.

The KamLAND study, which first detected geoneutrinos, measured the energy but not the direction of neutrinos from local nuclear reactors. After careful analysis, the geoneutrino spectrum was resolved at the low-energy end of the reactor spectrum. The data constrained the total abundance of uranium and thorium to values producing less than 60 terawatts at 99 percent confidence, with a central value of 16 terawatts.

This measurement is consistent with geochemical estimates, but background noise and reactor signal make the uncertainties too large to discriminate between models. Nonetheless, this initial result highlights potential geological benefits and experimental challenges. Further observations with more exposure, less noise, and less signal from nuclear reactors are needed at both continental and oceanic locations.

The magnitude and complexity of geoneutrino detection is a challenge for physicists, Earth scientists, and engineers. With the initial observation complete, refined measurements and new investigations are planned. The KamLAND project in Japan is preparing to filter radioactive contaminants from the scintillating fluid to reduce background noise. Projects in Italy and eastern

Canada (Table 1) should begin measuring continental radioactivity within the next few years. Additional projects, including an oceanic project near Hawaii, are under design. This marine project faces the challenge of adapting instrumentation for the ocean but, by minimizing the effects of continental crust, the project promises an important measurement of mantle and core radioactivity.

Because geoneutrino studies yield important new data on the bulk radioactive content of Earth's crust and mantle, these results are likely to significantly advance the understanding of our planet's composition and energetics.

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