Terrestrial Antineutrino Flux Measurements

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Electron antineutrinos accompanying the β-decays of long-lived isotopes of uranium, thorium, and potassium in the earth carry information about the quantity and distribution of these geologically important, heat-producing isotopes. This letter discusses terrestrial antineutrino flux measurements at both a continental and an oceanic site. A combined analysis of both measurements provides information on the partitioning of uranium and thorium between earth's mantle and crust and of the earth's radioactive heat. This direct information on the earth's deep interior represents a significant development in geochemistry and geophysics.

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The production and expected flux of electron antineutrinos from the β-decays of long-lived isotopes of uranium, thorium, and potassium in the earth have been discussed for decades [1]. Recently these terrestrial antineutrinos with energies above 1.8 MeV have been observed utilizing the inverse β-decay reaction on free protons in a large, monolithic, scintillating liquid detector [2]. With this observation an initial, non-constraining measurement of electron antineutrino flux from ^{238}U and ^{232}Th decays and radiogenic heat production within the earth has been provided.

The initial observation of terrestrial antineutrinos [2] motivates more detailed studies and indicates the necessity for refined experimental conditions. This letter describes measurements of ^{238}U and ^{232}Th concentrations averaged over geological reservoirs derivable from future observations at a pair of selected sites. It presents the exposures required at each site to produce measurements of a given precision based on a reference model. A combination of a continental and an oceanic site facilitates separate resolution of the uranium and thorium content of mantle and continental crust. This analysis is an important refinement of previously discussed multi-detector antineutrino spectroscopy [3]. Information provided by these measurements would represent a significant development in the knowledge of the composition and radioactive heating of the earth.

The present method of detecting terrestrial antineutrinos [2] is essentially the same as that used to discover the neutrino [4]. Spatially coincident signals from a prompt positron and a delayed neutron efficiently identify electron antineutrino absorption on free protons. This interaction has threshold energy of 1.8 MeV. The β-decay of ^{40}K falls below threshold requiring new techniques for detection. Isotopes in the decay series of ^{238}U and ^{232}Th have β endpoint energy above threshold. ^{228}Ac and ^{212}Bi in the ^{232}Th series have endpoint energies of 2.07 MeV and 2.25 MeV, respectively. ^{234}Pa and ^{214}Bi in the ^{238}U series have endpoint energies of 2.27 MeV and 3.27 MeV, respectively. Antineutrinos in the energy region above 2.3 MeV are due solely to ^{238}U. This permits separate

measurements of the fluxes due to ^{238}U and ^{232}Th with adequate detector energy resolution and calibration.

Background to the terrestrial antineutrino signal is due to reactor antineutrinos, spallation products from cosmic-ray muons, and radioactive contamination of the scintillating liquid [2]. Detectors located at least 1000 km from the nearest nuclear power plant, shielded by an overburden of at least 4000 m.w.e., and containing purified scintillating liquid reduces background to acceptable levels.

The detected terrestrial antineutrino flux spectrum depends on the quantity and distribution of ^{238}U and ^{232}Th within the earth and on geographic location. Geophysics and geochemistry guide the construction of terrestrial antineutrino flux models yet allow considerable variability [5]. Surface heat flow measurements estimate global power at 44±1 TW [6] giving an upper bound to radioactive heating and thereby the ^{238}U, ^{232}Th, and ^{40}K content of a cooling earth. Geochemistry governs the distribution of ^{238}U and ^{232}Th within the earth. Models predict concentrations in the continental crust roughly two orders of magnitude greater than in the mantle and zero in the core [7]. This results in a terrestrial antineutrino flux at least several times greater at a continental site than at an oceanic site. A comparison of the measured flux at these sites tests this fundamental geochemical paradigm.

Beyond a simple comparison of the total flux, combining analyses of the uranium and thorium fluxes at a continental site and an oceanic site yields more detailed geological information. The selected continental site is represented by the Homestake [8] mine near Lead, SD. The Henderson mine near Empire, CO. is a comparable site. Both continental sites are under consideration to host the Deep Underground Science and Engineering Laboratory. The selected oceanic site is offshore the west coast of Hawaii Island as identified by the Hanohano project [9]. All sites are shielded by an overburden of more than 4000 m.w.e. and subjected to a manageable reactor antineutrino flux.

The analysis combining terrestrial antineutrino flux measurements from the selected continental and oceanic sites is in terms of detector exposure in units of 10^{32} free proton years. Measurement precision depends on counting statistics scaling with the square root of exposure. Table I presents exposures required to produce 20% measurements of the ^{238}U and ^{232}Th antineutrino fluxes at the sites as predicted by a reference model [5]. These exposures are conservative since the reference model has relatively low concentrations of uranium and thorium.

Table I: The exposure in 10^{32} free proton-years required to produce 20% measurements of antineutrino flux due to ^{238}U (EC1) and ^{232}Th (EC2) at a continental and oceanic site as predicted by the reference model. Uncertainties are statistical. Flux measurements assume a detection efficiency of 0.7 and reduction due to neutrino oscillation by a factor of 0.57. Background is included from commercial nuclear reactors all operating with a duty cycle of 0.8.

Measured Quantity	**Exposure ($\times 10^{32}$ p-yr)**		
	Oceanic Site	**Continental Site**	
$\varphi(^{238}\mathrm{U})$	8.37±0.17	2.17±0.06	EC1
$\varphi(^{232}\mathrm{Th})$	77.3±2.6	16.1±0.4	EC2

^{238}U and ^{232}Th antineutrino fluxes are directly proportional to ^{238}U and ^{232}Th concentrations, respectively, when appropriately averaged over the sampled geological reservoirs. Therefore the

precision achieved in the measurement of the neutrino flux is correspondingly achieved in the isotope concentration. Isotope concentrations in the geological reservoirs govern radiogenic heat production. These concentrations, the mass of the reservoir, isotope activity, and energy deposition per decay [10] calculate heat production. ^{40}K contributes ~20% of the total radiogenic heat. Although ^{40}K is not detected, its contribution to the heat is derived from a presumably stable ratio of potassium to uranium (10,000 to 12,500) in all reservoirs. The reference model heats the mantle with 11 TW.

According to the reference model, 82% of the terrestrial antineutrino flux at the continental site originates from continental crust with the remainder from mantle. At the oceanic site 72% of the flux originates from mantle with the remainder from continental crust [11]. The continental detector primarily measures the uranium and thorium content of continental crust while the oceanic detector primarily measures the uranium and thorium content of mantle.

An analysis combining flux measurements from both the continental and oceanic detectors isolates flux contributions from continental crust and an assumed spherically symmetric mantle. Table II presents the resulting precision in the concentrations of ^{238}U and ^{232}Th, the thorium to uranium concentration ratio κ, and radiogenic heating for the continental crust and mantle using exposure combinations listed in Table I. This analysis yields more precise concentration and heat measurements for the continental crust than for the mantle because the reference flux at the continental site is more purely of continental origin than the reference flux at the oceanic site is purely of mantle origin.

Table II: The precision of ^{238}U, ^{232}Th, κ, and heat production measurements for the continental crust and mantle for the reference model [5] using exposure combinations listed in Table I. Heat calculations assume a U/K concentration ratio of ~8x10^{-5}.

EC1: 20% ^{238}U Flux Sensitivity		
Measured Quantity	**Mantle**	**C. Crust**
^{238}U conc.	0.31	0.27
^{232}Th conc.	0.94	0.71
κ = Th/U	3.20	0.93
Heat	0.42	0.34
EC2: 20% ^{232}Th Flux Sensitivity		
	Mantle	**C. Crust**
^{238}U conc.	0.10	0.10
^{232}Th conc.	0.33	0.28
κ = Th/U	0.39	0.35
Heat	0.16	0.14

Different geological models predict different concentrations of uranium, thorium, and potassium in the various earth reservoirs. Models with higher isotope concentrations produce correspondingly higher antineutrino fluxes and radiogenic heating. Flux measurements resulting from exposures given in Table I are benchmarks for comparing the reference model with geological models heating the mantle with 18 TW and 26 TW [12]. Table III presents the significance of the resolution when comparing measurements of uranium and thorium concentrations in the mantle and continental crust. The resolution is greatest for the measurement of uranium concentration in the mantle.

The preceding describes geologically important measurements of terrestrial antineutrino fluxes. It presents observation exposures required at both

continental and oceanic locations for producing 20% measurements of the fluxes due to uranium and thorium as given by a reference model [5]. It demonstrates the utility of combining oceanic and continental measurements to isolate concentrations of uranium and thorium, κ, and heat production in the mantle and continental crust with varying precision. Moreover, it shows how terrestrial antineutrino flux measurements can resolve geological models predicting different distributions and concentrations of uranium and thorium. These measurements provide important geological information lending insights to earth formation, composition, evolution, and dynamics.

Table III: The significance in number of sigma for resolving geological models with different levels of radiogenic heating in the mantle. The labels "cc" and "m" refer to continental crust and mantle, respectively. Significance is given for exposure combinations listed in Table I.

		EC1: 20% U	**EC2: 20% Th**
		18 TW vs. 11 TW	
cc	U	-1.4	-3.7
	Th	-0.2	-0.5
m	U	2.6	8.0
	Th	0.7	2.0
		26 TW vs. 11 TW	
cc	U	-1.7	-4.7
	Th	-0.1	-0.3
m	U	5.2	16.3
	Th	1.5	4.1

Measuring the terrestrial antineutrino flux both from continent and ocean is within current technological capability. Detectors with up to 4×10^{33} free proton targets are currently under consideration [13]. At this size observations for a combined analysis leading to 10% measurements of the uranium content and <20% measurements of radiogenic heat production of both mantle and continental crust are possible after deployments of just a few years. These direct measurements of the earth's deep interior would help constrain models of earth composition and dynamics leading to unprecedented advances in geochemistry and geophysics.

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