Measuring the Global Radioactivity in the Earth by Multidetector Antineutrino Spectroscopy

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We show that antineutrino ($\bar{\nu}_e$) spectroscopy in upcoming detectors in Italy and Japan can be used to measure the separate global abundances of ^{238}U and ^{232}Th, thus ~90% of the radiogenic heat in the Earth. Exploiting the unique advantage of their contrasting geological locations, they may also probe differences in U,Th areal densities in the continental and oceanic crusts and the mantle. Bearing directly on the interior of the whole Earth, such data can test, for the first time, the conceptual foundations of the geophysical structure, dynamics, and evolution of the present Earth. [S0031-9007(97)05047-3]

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The conceptual foundations of the Earth's geophysical structure and dynamics rest on a variety of surface observables (heat flow, electromagnetic currents, Earth and meteorite samples, etc.), and of interior probes (volcanic fallout, seismic sounding of gross structure, magnetism, etc.) [1]. A basic factor in the interior dynamics and the evolution of the present Earth is the radiogenic heat, ~90% of which comes from the decay of ^{238}U and ^{232}Th. With a U abundance and U to Th ratio evaluated for the solar system [2], the present Earth's radiogenic heat is set at ~16 TW, ~40% of the observed ~40 TW outflow on the Earth's surface. Models of the Earth [3] disperse ~50% of the total U,Th in the mantle (~2900 km thick) and concentrate the other ~50% in a thin, ~35 km crust under the continents. The oceanic crust is much thinner (~6.5 km) with a much smaller ($\times\frac{1}{20}$) U,Th abundance.

It is well known [4] that the heat produced in the interior of the Earth by α-β radioactivity may be measurable by detecting antineutrinos ($\bar{\nu}_e$) from the β decays, since essentially all the $\bar{\nu}_e$ reach the surface without interaction. Of the methods proposed towards this goal in the last 30 years [5,6], the most practical is the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ on the protons in a liquid scintillator, to detect ^{238}U and ^{232}Th, the only Earth nuclides that emit $\bar{\nu}_e$ over reaction threshold in their decay chains. The measured $\bar{\nu}_e$ flux yields the abundance of U,Th in the whole Earth, directly leading to the radiogenic heat of their decay. This reaction provides a coincidence tag $[e^+ \rightarrow (\sim 0.2\text{ ms delay}) + (n + p \rightarrow 2.2\text{ MeV } \gamma)]$ that severely suppresses background against $\bar{\nu}_e$ signals as small as events/yr in a kiloton-scale liquid scintillation detector sensitive to ~1 MeV signals [7]. The technology of such detectors is now highly developed for observing sub-MeV solar neutrinos [8]. In the same detector the tagged geo-$\bar{\nu}_e$ signal can be observed independently without any modification.

The first chance for terrestrial $\bar{\nu}_e$ research can be expected in two massive liquid scintillation detectors being built in Italy (Borexino [8] for solar neutrinos, etc., in 1999) and Japan (Kamland [9] for reactor ν physics, etc., in 2001). These two sites in particular, one on a continental crust and the other at the interface to an oceanic crust, bring unanticipated perspectives into view, viz., probing the *distribution* of U-Th in the Earth's crust. The task calls for sites with clear-cut, major geological contrast as in the present case. This unique, timely opportunity with impending detectors, thus urges immediacy for an in-depth study of the potential for "looking" into the Earth's interior by Italy-Japan based $\bar{\nu}_e$ spectroscopy.

As the technical detectability of geo-$\bar{\nu}_e$'s appears near, we investigated possible background interference from non-geo-$\bar{\nu}_e$'s, mainly from local/remote nuclear reactors. We also studied the impact of spectral uncertainties possible via ν oscillations of both geo- and reactor $\bar{\nu}_e$'s. Our work clarifies that interference from reactor $\bar{\nu}_e$'s is small (Borexino) to tolerable (Kamland); indeed, the predictable intensities and the well-defined spectral shape of reactor $\bar{\nu}_e$'s could serve to calibrate the detectors *in vivo*. Both detectors are sensitive to long baseline flavor oscillations of reactor $\bar{\nu}_e$'s. The resulting effects on the reactor signal however, do not obscure the geosignal or the inferences obtainable therefrom. Thus, the terrestrial U,Th can be measured *quantitatively* at both detectors. The global radiogenic heat is measured by the overall geo-$\bar{\nu}_e$ rate. We show further that U and Th can be *individually* determined by a spectral signature, leading to the first global transuranic chemical analysis of the Earth. A nonuniform crustal U,Th can be detected by a smaller geo-$\bar{\nu}_e$ flux at Kamland than at Borexino. Thus, for the first time, the structure of the global U,Th distribution predicted by current geochemical models appears testable by geo-$\bar{\nu}_e$ spectroscopy at two or more strategically sited $\bar{\nu}_e$ detectors.

The $\bar{\nu}_e$ flux that is effective at a point on the surface of the Earth from an internal source with an areal density N g/cm^2 is $\propto NG$, where G depends on the source geometry [6]. For a source uniformly dispersed in a sphere, $G = 1.5$. For a source distributed in a *thin* crustal shell of thickness c just below the surface, $G \approx \frac{1}{2}[1 + \ln(2/\varepsilon)]$ where $\varepsilon = c/R \ll 1$, R is Earth's radius, thus, $G_{\rm cc} = 3.45$ for a continental crust ($c =$ 35 km), $G_{\rm oc} = 4.3$ for an oceanic crust ($c = 6.5$ km) and $G_{\rm M} = 1.59$ for the mantle ($c = 2900$ km). Figure 1 shows the cumulative fractional flux at a surface point from sources in a crustal shell cap as a function of the line-of-sight $\lambda = r/R$ to the edge of the cap, for selected shell thicknesses. For a typical $c = 35$ km, sources within $r \sim 450$ km contribute $\sim 50\%$ of the flux, $\sim 90\%$ coming from $\lambda < 1$. Thus the flux at the detector is determined by the near source distribution (averaged on a scale of several 100 km) as well as by the remote sources (averaged over much larger intervals). Thus, at Kamland, at a crustal *interface*, half the azimuth angular range $\varphi \sim \pi$ lies in the Asian plate and the other half in the Pacific plate [10]. We thus expect the flux to be $\propto \frac{1}{2}(N_{\rm cc}G_{\rm cc} + N_{\rm oc}G_{\rm oc}) + N_{\rm M}G_{\rm M}$, showing sensitivity to a difference $N_{\rm cc} \gg N_{\rm oc}$ in the continental and oceanic crusts. In the extreme case that Japan is part of the ocean crust, the flux tends to values $\propto N_{\rm oc}G_{\rm oc} + N_{\rm M}G_{\rm M} \approx N_{\rm M}G_{\rm M}$, essentially from the mantle U,Th only. In contrast, Borexino sees mostly continental plates (extending far to the east and south over $\varphi \sim 3\pi/2$ and up to 1000 km in the northwest quadrant) [10]; thus a flux tending to values $\propto N_{\rm cc}G_{\rm cc} + N_{\rm M}G_{\rm M} \approx N_{\rm cc}G_{\rm cc}$. The source geometries in the Earth's structures thus influence the flux at the detector according to the geostructures of the near and remote vicinity of the site and allow us to probe the crustal source distribution.

The geo-$\bar{\nu}_e$ spectrum steps from β-decay branches with $E(\beta_{\rm max}) > 1.8$ MeV ($= \bar{\nu}_e + p$ threshold) from ^{234}Pa and ^{214}Bi in the chain decay of ^{238}U, and from ^{228}Ac, ^{212}Bi, and ^{208}Tl in the decay of ^{232}Th. The Coulomb fields of these high Z nuclei pile up $\bar{\nu}_e$'s towards the high energy end, favoring their detectability. The specific $\bar{\nu}_e$ emissions above threshold are $n({\rm U}) = 0.40$ per decay; $n({\rm Th}) = 0.156$ per decay. The signal energy is $E({\rm MeV}) = E(\bar{\nu}_e) - 1.8 + 2m_ec^2 = E(\bar{\nu}_e) - 0.78$.

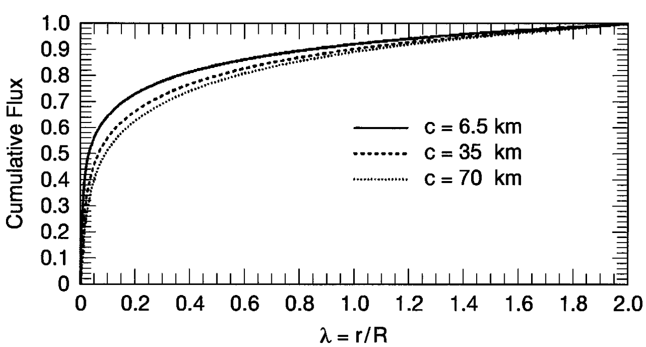

FIG. 1. Cumulative flux at a surface point of a sphere from sources in a crustal shell of thickness c just below the surface, within a line-of-sight λ for different values of the shell thickness.

Thus, even "at threshold", $\bar{\nu}_e$'s produce an e^+e^- signal of 1.02 MeV. The ^{232}Th spectrum is limited to $E(\bar{\nu}_e) < 2.24$ MeV while that from ^{238}U extends to $E(\bar{\nu}_e) = 3.26$ MeV. Thus, $\bar{\nu}_e$ events in the signal window 1.5–2.5 MeV measure U geo-$\bar{\nu}_e$'s exclusively. This signature allows *individual* assay of the Earth's U and Th abundance.

The $\bar{\nu}_e$ spectrum can be calculated with NG g/cm^2, S, the specific activity (U : 1.24×10^4 Bq/g; Th : 0.40×10^4 Bq/g) and the integral $I = \int \eta(E)\sigma(E)\,dE = 2.52 \times 10^{-44}$ cm^2/U decay; 0.51×10^{-44} cm^2/Th decay, where $\eta(E)$ is the $\bar{\nu}_e$ spectrum per decay and $\sigma(E)$, the $\bar{\nu}_e + p$ reaction cross section [11]. The signal yield $Y = \sum_{\rm geo}\sum_{\rm U\text{-}Th}(NGSI)$/s/target proton where $\sum_{\rm geo}$ sums over geostructural components relevant to that site. Model I (Table I) is a generally representative set [3] of N without claim to accuracy of detail. Practical geo-$\bar{\nu}_e$ spectra are shown in Fig. 2 for the "standard" set of N and other sets (see below). The two peaks of the U-Th chemical signature in the 1–2.5 MeV window can be resolved to extract the U, thus also the Th component.

The basic background for the geosignal is $\bar{\nu}_e$ from other sources: nuclear reactors, solar ν conversion to $\bar{\nu}_e$ via Majorana magnetic moments [12], relics of past supernovae [6], and muon decays in the atmosphere. Only the first leads to sizable signals in the geo-$\bar{\nu}_e$ window.

Borexino and Kamland are in areas of high concentrations of nuclear power. European reactors north of the Alps produce 470 GW thermal power [13], some $\sim$800 km from Borexino (Italy itself has no power reactors). In Japan they are much closer to Kamland, at about 160 km, with a total power of $\sim$130 GW (thermal). With the known location and power of each reactor, a mean fuel composition [14], the known number of $\bar{\nu}_e$/fission and their spectrum [11], and a nominal efficiency of $\sim$80%, the $\bar{\nu}_e$ spectrum observable at each detector was calculated as shown in Fig. 2. In both detectors, the geo-$\bar{\nu}_e$ signal clearly stands out from the reactor $\bar{\nu}_e$ spectrum that extends well beyond the geo-$\bar{\nu}_e$ window. This allows reliable extrapolation of its contribution since the reactor $\bar{\nu}_e$ spectral shape is precisely calculable [11]. The intensity of this flux can be monitored during experimental runs, using periodic data from power stations [13]. The reactor $\bar{\nu}_e$ thus acts as a reliable *calibrating beacon*, mandatory in a new technique set to explore the uncharted interior of the Earth with weak signals.

With a nonzero mass and mixing to other flavors $\bar{\nu}_{\mu,\tau}$, geo- and reactor $\bar{\nu}_e$'s can be converted to $\bar{\nu}_{\mu,\tau}$ which are undetectable by the $\bar{\nu}_e + p$ reaction. This effect can distort $\bar{\nu}_e$ spectra in Fig. 2, possibly obscuring the geosignal. The $\bar{\nu}_e$ survival spectrum is $F^C(E_\nu) = \int F(E_\nu, r)\{1 - \sin^2 2\theta \sin^2[(r/4)\Delta m^2/E_\nu]\}\,dr$, ($r$ is the source distance, θ is the mixing angle, $\Delta m^2 = m_1^2 - m_2^2$; $m_{1,2}$ are the eigenstate masses). $F^C(E_\nu)$ was calculated for a wide range of parameters, especially in the range $\Delta m^2 = 10^{-2} - 10^{-5}$ eV^2, $\sin^2 2\theta > 0.6$, indicated as likely by solar and atmospheric neutrinos [15] and where

TABLE I. Abundances of ^{238}U and ^{232}Th and signal rates in model I (Th/U abundance = 4; U-Th radiogenic heat = 16 TW); Y = Rate/10^{32} p/yr; Y(Kamland; 1 Kton mineral oil = 0.86×10^{32} p) = 0.86 Y(Japan); Y(Borexino; 300 ton pseudocumene = 0.18×10^{32} p) = 0.18 Y(Italy).

Feature	Mass 10^{25} g	U ppm	N(U) g/cm^2	Y U	Y Th	Y Total
CC	2.3	1.8	27.5	93.5	24.8	118
OC	0.6	0.08	0.13	0.56	0.15	0.71
M	400	0.01	7.76	12.2	3.2	15.4
Ia Japan [$Y_{\rm tot}${1/2(CC + OC)} + M]						75
Ia' Japan [$Y_{\rm tot}$(OC + M)]						16
Ia Italy [$Y_{\rm tot}$(CC + M)]						134
Ib (uniform crustal U/Th) Japan						50
Ib (uniform crustal U/Th) Italy						50
IIa,b (40 TW U/Th radiogenic heat)						2.5Y (Ia,b)

spectral changes can occur in the three different long base lines involved in the problem. Figure 3 shows typical results with $\sin^2 2\theta = 0.7$, $\Delta m^2 = 1.7 \times 10^{-5}$ eV^2 suggested by solar neutrinos [15]. The main effect is a large (~50%) signal reduction. Distortions do occur in the geosignal region but they are small and correctable by fits to the whole spectrum. Inferences from the geosignal are not likely to be obscured by $\bar{\nu}_e$ oscillations.

Non-$\bar{\nu}_e$ background arises from events mimicking the $\bar{\nu}_e + p$ coincidence tag. Single events can do this only by chance, thus, γ-ray shielding and material purity are far less critical here than for solar neutrino studies without benefit of a tag. Even for U at 10^{-14} g/g or Rn at 0.2 mBq/ton (×100 Borexino design values), at worst, ~3 (false tags/yr)/kton occur due to random coincidences. The only correlated background from trace activity is the delayed β-α coincidence of ^{214}Bi in the ^{238}U(^{222}Rn) chain, which is eliminated by a $>20\sigma$ deviation of the (quenched) α-scintillation signal out of the tag window and by α discrimination by pulse shape. Cosmic rays can induce activities that emit β-n cascades inseparable from the $\bar{\nu}_e$ tag. With only C,H in the target, the only possible activities are ^{8}He, ^{9}Li, and ^{11}Li with $\tau < 260$ ms; they can be removed efficiently by a veto signal of the initiating μ or n/recoil proton. Fast neturons mimic the tag by an initial recoil-proton signal followed by n capture after thermalization; they can be identified by the pulse shape of the initial recoil-proton signal. Due to the low $\bar{\nu}_e$ signal rates however, we continue to search possibilities for rare, uncommon types of false tags.

The total geo-$\bar{\nu}_e$ rate at Borexino yields the global radiogenic *heat* from U,Th via the average heat/decay of 47.3 MeV/U and 39.6 MeV/Th (totaling ~16 TW in model I). The *relative* rates at the two sites probe the global *distribution* of U and Th. Large differences are expected in the geo-$\bar{\nu}_e$ fluxes at the two sites in models Ia,Ia$'$ with grossly unequal U,Th in the continental and oceanic crusts.

A main result from the geo-$\bar{\nu}_e$ signal spectrum is the Th/U ratio. Adopted here as Th/U ≈ 4 for all the geostructures (≈solar value = 3.63 [2,3]), it could be altered by differences in the segregation chemistry of U and Th during the evolution of the Earth's mantle and crust. Thus, the Th/U ratio as well as *different* values of it at Borexino and Kamland (especially if the latter is on the oceanic crust itself, thus seeing mostly the *mantle*), are key pointers to the Earth's dynamical history.

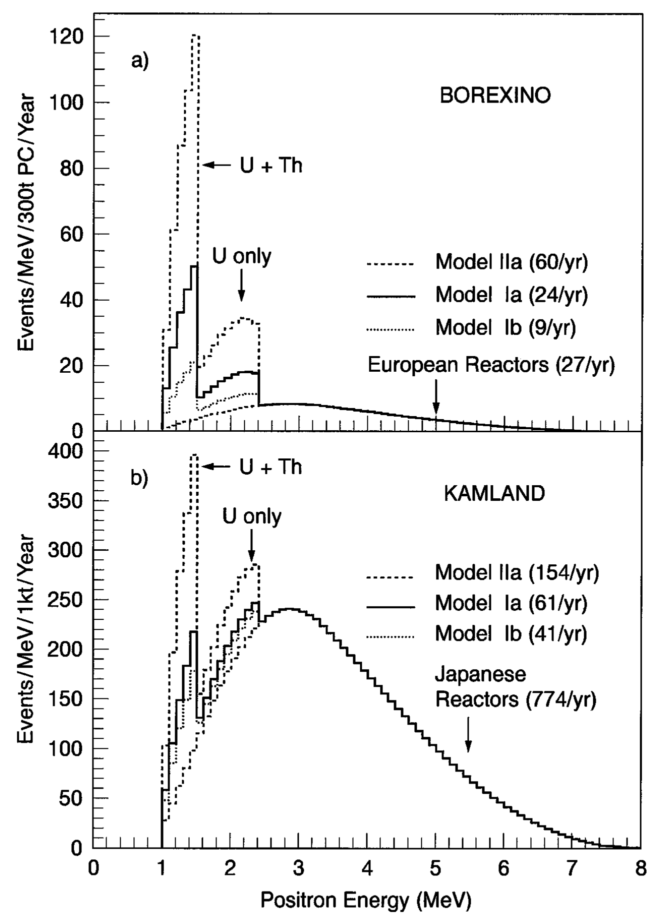

FIG. 2. $\bar{\nu}_e$ (positron) signal spectra from the Earth and from nuclear reactors at Borexino (a) and at Kamland (b). The signal rates point to several years of measurement for data of statistical significance to different aspects of geophysical interpretation.

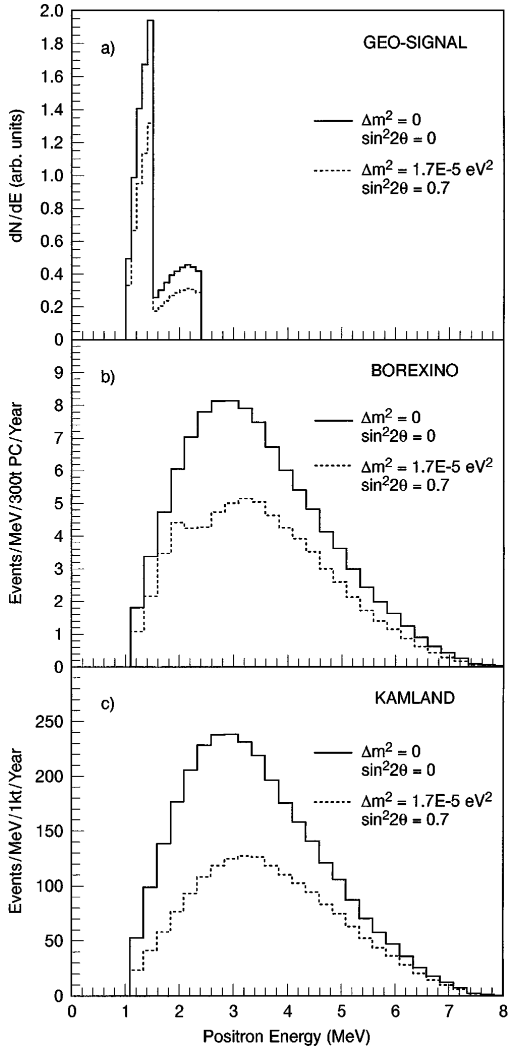

FIG. 3. $\bar{\nu}_e$ spectra with/without flavor conversion for geo-$\bar{\nu}_e$ (a) and reactor $\bar{\nu}_e$ at Borexino (b) and at Kamland (c).

The central geophysical model Ia produces quantitatively measurable geo-$\bar{\nu}_e$ signal rates and spectra (Fig. 2). The play of models on these rates can be seen from bounds set by (possibly) artificial assumptions set at theoretical limits of geofeatures. Keeping the Th/U ratio the same in this exercise, model Ib redistributes the *crustal* U,Th of Table I uniformly in a 35 km crust under the oceans *and* continents. This depletes the source density in the continental crust by $\times 3.4$ and equalizes the fluxes at Borexino and Kamland. Ratios of geo-$\bar{\nu}_e$ signal rates and the derived fluxes at these two sites, thus probe the U,Th distribution in the Earth's interior sensitively.

Models IIa,b assume that all the limiting 40 TW heat from the Earth is U,Th radiogenic. This increases all the rates by $\times 2.5$. Geo-$\bar{\nu}_e$ fluxes *larger* than this limit can occur *only* by serious alteration of the source distribution, such as enrichment of the continental crust at the expense of the mantle. The increase in the flux occurs by changing a "ball"-type of source in the mantle to a "shell"-type source in the crust. The theoretical maximum of the geo-$\bar{\nu}_e$ flux with 40 TW radiogenic heat and *all* the Earth's U-Th in the *continental crust* is $\approx 2.5 \times [(2CC/(CC + M)] \approx 4.5$ times the flux of Ia(Italy) in Table I. The range of the absolute and relative geo-$\bar{\nu}_e$ signals observable at Borexino and Kamland can thus test the Earth's geophysical-chemical structure and its evolution, at its foundations, and in the detailed modeling.

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