Geoneutrino Observation

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Geoneutrino

Geoneutrino as a new probe to observe Earth’s interior
Predicted more than 50 years ago
Geoneutrino observation has been done with KamLAND and Borexino.
Geoneutrino as a new probe to observe Earth’s interior
Seismic wave and geoneutrino

- Seismic wave is the strongest tool to see Earth’s interior, but it has been a lonely tool for long time.

- Geoneutrino is the first independent, compensating, synergetic companion, which will provide new information, such as heat source amount, and chemical composition.
Geo-neutrino source: \( ^{238}U \) series

\[ \beta \text{ decay: } e.g. \quad ^{214}\text{Bi} \rightarrow ^{214}\text{Po} + e^- + \bar{\nu}_e \]

source of geoneutrino: radioactive element in the crust and mantle

\( \beta \) decay:

\( ^{214}\text{Bi} \rightarrow ^{214}\text{Po} + e^- + \bar{\nu}_e \)

electron antineutrino
Geo-neutrino source: $^{232}\text{Th}$ series
Geoneutrino from $^{238}\text{U}$, $^{232}\text{Th}$, $^{40}\text{K}$

Half life

$^{238}\text{U}$

$^{232}\text{Th}$

$^{40}\text{K}$

Electron antineutrino ($\bar{\nu}_e$) is detected with $\bar{\nu}_e + p \rightarrow e^+ + n$ (inverse beta decay)
The expected $^{238}\text{U}$, $^{232}\text{Th}$, and $^{40}\text{K}$ decay chain electron anti-neutrino energy distribution. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to $^{40}\text{K}$ electron antineutrinos.
Geoneutrino observation with KamLAND
Kamoka Liquid scintillator Antineutrino Detector

Japan, US, Europe collaboration lead by RCNS, Tohoku U.

Gifu prefecture, Hida city, Kamioka mine about 1000 m underground (2,700 m water equivalent) to avoid cosmic-ray background

Northern Japanese Alps
Geoneutrino flux at KamLAND site

KamLAND: 1000-ton ultrapure liquid scintillator

Inner Balloon installed in 2011
1879 phototubes cover 34% of the inner surface of the spherical stainless steel tank (18-m diameter)
Kamioka Liquid Antineutrino Detector

- Kevlar ropes
- Water tank
- Balloon
- Buffer oil
- Phototubes
- Liquid scintillator
- Prompt signal: 0.9~8MeV
- Delayed signal: 2.2MeV
- Nhit
- ~200μs
- time
- Balloon 13mϕ
Contribution to the settlement of the solar neutrino problem (30-year problem)

The settlement was an important breakthrough, and should be basics of all fluxes measurement with Borexino.

Nuclear power reactors

Sun

Super-Kamiokande

Solar neutrino deficit (1970’s)
Solar or neutrino problem? (30 years)
Settlement (2002) with neutrino oscillation

(*1) neutrinograph of the sun by Super-K, (*2) hep-ph/0406294
First result from KamLAND (2002)

$\bar{\nu}_e$ disappearance: 99.95 % C.L.
Geoneutrino first results in 2005

152 events observed
“signal” $25^{+19}_{-18}$

Data-set: 749.1 days

Fiducial: 5 m radius

Systematic uncertainty

(Data from Nature 436, 28 July 2005)
Geoneutrino observation with KamLAND (the latest published data (2013))
Data set

- "Reactor on-off antineutrino measurement with KamLAND", Phys. Rev. D 88 033001 (2, August, 2013)
- March 9, 2002 – November 20, 2012 (2991 days live-time)
- Data set is divided into 3 period

![Graph showing rate (events/day) over time with labels for Period 1, Period 2, Period 3, and key events like 2011 earthquake and KamLAND-Zen construction. The graph also highlights scintillator purification]
Energy calibration

Cherenkov-Birks model
Data reduction (event selection)

- Fiducial volume (event within which is considered available): \( R < 6 \text{ m} \) (mini balloon cut for period 3)

- Delayed coincidence:
  - Prompt energy: 0.9 – 8.5 MeV
  - (neutrino energy: 1.7 – 9.3 MeV)
  - Delayed energy: 1.8 – 2.6 MeV, or 4.4 – 5.6 MeV
  - (peak at 2.2 MeV, and 4.9 MeV)
  - Spatial correlation: < 2.0 m
  - Time correlation: 0.5 – 1000 µs

- Additional selection to suppress accidental coincidence further, based on probability densities of accidental coincidence and real signal
Kamioka Liquid Antineutrino Detector

- Kevlar ropes
- Water tank
- Buffer oil
- Liquid scintillator
- Balloon
- Phototubes
- Prompt signal: 0.9~8MeV
- Delayed signal: 2.2MeV
- $N_{\text{hit}}$ time: $\sim 200 \mu s$
- Balloon 13mφ
Prompt energy (neutrino energy – 1.8 MeV) spectrum: all period

- 116 ±28\(^{-27}\) geoneutrino events are detected (U/Th = 3.9 fixed, energy spectrum, time variation included, unbinned, all 3 periods)
- U: 116 events
- Th: 8 events with U, Th free fitting

FIG. 6 (color). Prompt energy spectrum of the \(\bar{\nu}_e\) events in the low-energy region for all data-taking periods. Bottom panel:
Energy spectrum of each period

- $^{13}$C($\alpha,n)^{16}$O background is reduced by a factor of 20 in Period 2. (by scintillator purification)

- Reactor background decreased in Period 3
Time variation: 0.9 – 2.6 MeV (geoneutrino region)

- Data (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent, not consistent with reactor + b.g. only (colored curve)
- Data are on the unit slope with finite displacement, indicating constant contribution from geoneutrinos!
Time variation: 0.9 – 2.6 MeV (geoneutrino region)

Nova (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent, not consistent with reactor + b.g. only (colored curve)

Data are on the unit slope with finite displacement, indicating constant contribution from geoneutrinos!
**Time variation: 0.9 – 2.6 MeV (geoneutrino region)**

Data (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent, not consistent with reactor + b.g. only (colored curve)

Data are on the unit slope with finite displacement, indicating constant contribution from geoneutrinos!
The efficiency-corrected best-fit value of the geo-colored bands. The observed event rate for each group is plotted at the exposure-weighted expected event rate within the group.

For KamLAND, or a total antineutrino flux including all flavors of the model expectation (gray line) are drawn for comparison. The contribution of geo-neutrinos in (b) is negligible. The oscillation analysis of Ref. [Fig. 7(b)], we find that the null hypothesis is disfavored at 90% C.L., an improvement of a factor of 1.7.

VII. CONSTRAINTS ON EARTH MODELS

The KamLAND data also tests the hypothesis of a core-primordial origin of Earth's O. Due to the generally low event rate observed for Th, the result is consistent with a core-primordial origin of Earth's O. As a consequence, we find a null hypothesis of core-primordial origin of Earth's O at 95% C.L., assuming a constant power output over the duration of the experiment.

Data (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent, not consistent with reactor + b.g. only (colored curve).

Data are on the unit slope with finite displacement, indicating constant contribution from geoneutrinos!
Data (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent, not consistent with reactor + b.g. only (colored curve)

Data are on the unit slope with finite displacement, indicating constant contribution from geoneutrinos!
The efficiency-corrected best-fit value of the geoneutrino bands. The observed event rate for each group is plotted at the exposure-weighted expected event rate within the group.

The ratio of 3.9 (corresponding to a flux ratio of 0.85) is consistent with the expectation from the geological reactor power of Ref. [1]. This result corresponds to a consistent fit of geo + backgrounds (colored line), and reactor + backgrounds + geo, grey curve) are consistent, not consistent with reactor + backgrounds only (colored curve).

Data (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent, not consistent with reactor + b.g. only (colored curve).

Data are on the unit slope with finite displacement, indicating constant contribution from geoneutrinos!

Expected Rate of reactor + other b.g. (without geonu)
Time variation: 2.6 – 8.5 MeV (reactor region)

Data (solid circles) and expected rate (reactor + b.g. + geo, grey curve) are consistent

Data are on the unit slope with zero displacement (right panel): quite consistent again!
Time variation (reactor and geo regions)

(a) 0.9-2.6 MeV

(b) 2.6-8.5 MeV

FIG. 2 (color). Time evolution of expected and observed rates at KamLAND for periods 1-3.

- **Period 1**: 2002-2004
- **Period 2**: 2005-2007
- **Period 3**: 2008-2012

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9-2.6 MeV</td>
<td>1-2-3</td>
</tr>
<tr>
<td>2.6-8.5 MeV</td>
<td>1-2-3</td>
</tr>
</tbody>
</table>

- **KamLAND data**
- **Expected reactor \( \nu_e \) + backgrounds + geo \( \nu_e \)**
- **Expected reactor \( \nu_e \) + backgrounds**
- **Expected reactor \( \nu_e \)**

The observed event rate for each group is plotted at the exposure-weighted expected event rate within the group. The separation of U and Th contributions from radioactive decays is calculated using conversion factors. The joint confidence intervals for the sum of U and Th geo rates are calculated from the reference model of Ref. [3].

The ratio of U to Th geo concentrations is constrained to 3.9 (corresponding to a flux ratio of 0.85), as this result agrees with the expectation from the geological model of Ref. [4].

The natural nuclear reactor in the Earth's core is of particular importance for understanding quantitative estimates of the heat production by radioactive elements. The KamLAND data also test the hypothesis of a constant total antineutrino flux including all flavors.
Comparison with the reference model

▲ U, Th event rates are consistent with the reference model
▲ With fixed Th/U = 3.9, total geoneutrino events are $116^{+28}_{-27}$, excluding no geoneutrino hypothesis with more than 4 sigma
▲ Uranium neutrino positive: Th/U < 19 (90% C.L.)
Jaupart et al. (2007) assumed)

4

depends on the modelling of the geology. We account for crustal

fully radiogenic hypothesis is disfavoured at the distributing the source as far from the detectors as possible. The fully radiogenic model with the observed geoneutrino flux by hypothesis' or alternatively, by putting all of the U and Th at and gemn at the moT zLc consistent with gej from the ySE modele

origine Other models require convective Urey ratios up to allowing for a substantial fraction of the heat to be of primordial

referred to as the 'convective Urey ratio'

the crust contribution is subtracted for clarity.

iji

significantly smaller crustal contribution. zombining the these locations and Hawaiic as an example of an oceanic site with a and Gran Sasso experimental sites along with the predictions for Figure ka shows the measured geoneutrino fluxes at the Kamioka

KamLAND Borexino

0

Kamioka Gran Sasso Hawaii

\( \tilde{\nu}_e \) flux (x 10^{6} \text{ cm}^{-2} \text{s}^{-1})

\( \tilde{\nu}_e \) flux (x 10^{6} \text{ cm}^{-2} \text{s}^{-1})

Kamioka Gran Sasso

Kamioka Gran Sasso

\( \tilde{\nu}_e \) flux

fully radiogenic

Radiogenic heat production

from 238U and 232Th (TW)

\( \tilde{\nu}_e \) flux

\( \tilde{\nu}_e \) flux

``Partial radiogenic heat model for Earth revealed by geoneutrino measurements”, Nature Geoscience 17, July 2011 (only this figure is from our previous publication that does not include low reactor period after 2011)

\( \text{\large \text{\#}} \)

Fully radiogenic model (homogeneous mantle) is excluded with 98% C.L. (total heat flow 46±3 TW (Jaupart et al. 2007) assumed)
Comparison with other models

``convective Urey ratio'' (radiogenic heat source in the mantle) / (total heat source): 0.09 – 0.42 (68 % C.L.) → consistent with BSE model (0.3), primordial heat source necessary

Geodynamical model that assumes relatively high Urey ratio, is becoming to be disfavored
Geoneutrino observation with Borexino

PHYS. REV. D 101, 012009 (2020)

“Comprehensive Geoneutrino Analysis with Borexino” (really comprehensive. All geoneutrino researchers are recommended to read this original paper)
Laboratori Nazionali del Gran Sasso LNGS (Italy)

3800 m.w.e

Far away from reactors ~ 1200 km

Ultrapure liquid scintillator (so pure as to measure all fluxes of solar neutrinos)

FIG. 2. Scheme of the Borexino detector.

PHYS. REV. D 101, 012009 (2020)
Particle ID (α v.s. β/γ)

Particle identification (ID) using pulse shape (time profile) difference of scintillation light has been improved.

![Graph showing particle identification](image)

**FIG. 11.** Distributions of the Gatti (G) (a) and the multilayer perceptron (MLP) (b) α/β discrimination parameters for $^{214}$Bi($\beta^-$) (dashed line) and $^{214}$Po(α) (solid line) events.
Results

- energy spectra of IBD (inverse beta decay) events (electron antineutrino events)
- Geoneutrino measurement achieved
- analyses with Th/U ratio fixed and free agreed

FIG. 48. Results of the analysis of 154 golden IBD candidates. (a) Spectral fit of the data (black points with Poissonian errors) assuming the chondritic Th/U ratio. The total fit function containing all signal and background components is shown in brownish-grey. Geoneutrinos (blue) and reactor antineutrinos (yellow) were kept as free fit parameters. Other nonantineutrino backgrounds were constrained in the fit. (b) Similar fit as in (a) but with 238U (dark blue) and 232Th (cyan) contributions as free and independent fit components. (c) The best fit point (black dot) and the contours for the 2D coverage of 68, 99.7, (100–5.7 × 10−5)% and (100–1.2 × 10−13)% (corresponding to 1, 3, 5, and 8σ, respectively), for Ngeo versus Nrea assuming Th/U chondritic ratio. The vertical lines mark the 1σ bands of the expected reactor antineutrino signal (solid—without “5 MeV excess,” dashed—“5 MeV excess”). For comparison, the star shows the best fit performed assuming the 238U and 232Th contributions as free and independent fit components. (d) The best fit (black dot) and the 68, 95.5, and 99.7% coverage contours (corresponding to 1σ, 2σ, and 3σ contours) NTh versus NU. The dashed line represents the chondritic Th/U ratio.
Various BSE (Bulk Silicate Earth) models are tested

Borexino data (black line and grey band) shows relatively high geoneutrino signal

FIG. 50. Comparison of the expected geoneutrino signal $S_{\text{geo}}(U + Th)$ at LNGS (calculated according to different BSE models, see Sec. V B) with the Borexino measurement. For each model, the LOC and FFL contributions are the same (Table VI), while the mantle signal is obtained considering an intermediate scenario [Fig. 16(b)]. The error bars represent the 1σ uncertainties of the total signal $S(U + Th)$. The horizontal solid back line represents the geoneutrino signal $S_{\text{geo}}^{\text{med}}$, while the grey band the $I_{\text{obs}}^{68\%\text{full}}$ interval as measured by Borexino.
Results released so far

Results released so far are all consistent and uncertainty has been improved greatly.

FIG. 51. Comparison of the geoneutrino signal $S_{\text{geo}}(U + \text{Th})$ at LNGS as measured by Borexino. Blue circles indicate the results from 2010 [16], 2013 [17], and 2015 [18], while the red square demonstrates the current analysis.

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Mantle contribution significant

- Mantle contribution is clearly significant, with careful estimation of crust contribution
- In the lower panel, “0” (no mantle contribution hypothesis) is outside of the 99.7% confidence interval.

FIG. 52. (a) Spectral fit to extract the mantle signal after constraining the contribution of the bulk lithosphere. The grey shaded area shows the summed PDFs of all the signal and background components. (b) The likelihood profile for $N_{\text{mantle}}$, the number of mantle geoneutrino events. The vertical solid red line indicates the best fit, while the vertical solid black and green lines indicate the median and mean values of the distributions, respectively. The vertical dashed/dotted lines represent the 68%/99.7% confidence intervals of the distribution.
Researches by theorists and geologists
Combined analyses

- Combined analyses using both KamLAND and Borexino data are performed involving theorists and geologists.
- In an example shown here, various cases of constraints (e.g. Th/U ratio) are tested, and stability of conclusions and consistency between two data are carefully examined.

![Combined analyses figure](image)

**Fig. 4** (color online). KamLAND (KL) and Borexino (BX) geoneutrino analysis in the plane charted by the total rate $R(\text{Th + U})$ and by the mass abundance ratio Th/U. The curves represent $1\sigma$ contours ($\Delta \chi^2 = 1$) around the best-fit points (thick dots). From top to bottom, the degrees of freedom decrease from $N_D = 4$ to $N_D = 1$, as reported in Table I.

**Table I.** Summary of adopted degrees of freedom and constraints.

<table>
<thead>
<tr>
<th>$N_D$</th>
<th>Constraints</th>
<th>$R(\text{Th + U})_{\text{KL}}$</th>
<th>$\langle \text{Th/U} \rangle_{\text{KL}}$</th>
<th>$R(\text{Th + U})_{\text{BX}}$</th>
<th>$\langle \text{Th/U} \rangle_{\text{BX}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>none</td>
<td>free</td>
<td>free</td>
<td>free</td>
<td>free</td>
</tr>
<tr>
<td>3</td>
<td>$\langle \text{Th/U} \rangle_{\text{BX}} = \langle \text{Th/U} \rangle_{\text{KL}}$</td>
<td>free</td>
<td>free</td>
<td>free</td>
<td>free</td>
</tr>
<tr>
<td>2</td>
<td>$\langle \text{Th/U} \rangle_{\text{BX}} = \langle \text{Th/U} \rangle_{\text{KL}}$ and $R_{\text{BX}} = 1.15R_{\text{KL}}$</td>
<td>free</td>
<td>free</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>1</td>
<td>$\langle \text{Th/U} \rangle_{\text{BX}} = \langle \text{Th/U} \rangle_{\text{KL}} = 3.9$ and $R_{\text{BX}} = 1.15R_{\text{KL}}$</td>
<td>free</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Near future experiments
Liquid scintillator detector in Canada. Successor of SNO who measured all-flavor solar neutrino for the first time.

Construction completed. We have to stay tuned.

The SNO+ detector filled with LAB. Credit: SNO+ Collaboration
JUNO

Multipurpose neutrino detector in China. (especially reactor neutrino oscillation, to further improve Daya Bay achievements)

Largest liquid scintillator detector (20 kton) when completed

Construction started. We look forward to their works

http://juno.ihep.cas.cn/
Jinping

- Plan of multipurpose neutrino detector in China
- Largest overburden (2400 m)
- To measure geoneutrinos from Himalaya (largest continental crust)

Fig. 3. (color online) The conceptual design for a cylindrical neutrino detector at Jinping. Two detectors are needed to reach the desired mass requirement.

Chinese Physics C Vol. 41, No. 2 (2017) 023002

http://jinping.hep.tsinghua.edu.cn/
Geoneutrino measurements by KamLAND and Borexino demonstrated it is a probe to see Earth’s interior together with seismic wave.

New experiments are coming soon. We are looking forward to them.