Using Neutrinos to Study the Earth
- Geoneutrinos -

1. Neutrino Geophysics
2. KamLAND Results
3. Near Future Prospects (Borexino, SNO+, …)
4. Far Future Dreams

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Geoneutrinos

Generated by beta-decay chain of natural isotopes (U, Th, K)

\[ ^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\ ^{4}\text{He} + 6\ e^- + 6\ \bar{\nu}_e \]

\[ ^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\ ^{4}\text{He} + 4\ e^- + 4\ \bar{\nu}_e \]

\[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} + \ e^- + \bar{\nu}_e \]

With organic scintillator, detected by inverse-beta decay reaction

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

No directional info.
Threshold: 1.8 MeV

No directional info.

Discovery of radioactive isotopes in the Earth??

![Graph showing luminosity vs. antineutrino energy](image)
Geoneutrinos: A New Tool to Explore the Earth Interior

- Generated by radioactivity inside the Earth
  \[ ^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\ ^4\text{He} + 6\ e^- + 6\ \bar{\nu}_e + 51.7\ [\text{MeV}] \]
  \[ ^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\ ^4\text{He} + 4\ e^- + 4\ \bar{\nu}_e + 42.7\ [\text{MeV}] \]
  \[ ^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \bar{\nu}_e + 1.3\ [\text{MeV}] \]

- Radiogenic heat dominates Earth energetics
  - Measured terrestrial heat flow \( \sim 44\ \text{TW} \)
  - Estimated radiogenic heat (model prediction): \( ^{238}\text{U} \sim 8\ \text{TW} / ^{232}\text{Th} \sim 8\ \text{TW} / ^{40}\text{K} \sim 3\ \text{TW} \)

- The only direct geochemical probe
  - The deepest borehole reaches only \( \sim 12\ \text{km} \)
  - The deepest rock sample originates \( \sim 200\ \text{km} \)
Heat Producing Element (HPE) and Energy Balance

Heat Release from the Surface

- 24774 bore-hole measurements
- Corrections of hydrothermal circulation

\[ 44.2 \pm 1 \text{ TW Total Heat Flux} \] (Recent Challenge 31 \pm 1 \text{ TW})

- Core heatflow (solidification etc.) estimated 5\text{~}15 \text{ TW} ???
- Secular cooling 18 \pm 10 \text{ TW} ???

The Ingredient of the Earth
CI-Chondrite Meteorite

tells the composition of the Bulk Silicate Earth (BSE)
(fundamental paradigm of geochemistry)
[McDonough et al, Chem.Geo.120,223 (1995)]

\[ \sim 20 \text{ TW Radioactive Heat} \]
(U: \sim 8 \text{ TW}, Th: \sim 8 \text{ TW}, K: \sim 3 \text{ TW})
Earth Evolution (Differentiation) and Present Structure

- **Continental Crust**
- **Upper Mantle**
- **Lower Mantle**
- **Outer Core (liquid)**
- **Inner Core (solid)**
- **Metallic Earth**
- **Silicate Earth**
- **Oceanic Crust**
- **Mid-Ocean Ridge**
  - Oceanic crust is being created by partial melting of mantle
  - *Incompatible* elements (U, Th, K) extracted
- **Subduction Zone (Japan etc)**
  - Continental crust is being created by partial melting of oceanic crust and mantle
  - *Incompatible* elements (U, Th, K) extracted
- **Core**
  - High density Fe-Ni alloy
  - *Lithophile* elements (U, Th, K) are hardly (almost never) contained

**Result of 4.5Ga Planetary Evolution**
- Half of U and Th are contained in Continental Crust
- Mantle ???
  - uniform or layered, depleted or recycled, something on the bottom ???
Start Point: A Reference Earth Model

- BSE composition by [McDonough1999]
- Crustal composition by [Rudnick et al. 1995]
- Crustal thickness by CRUST 2.0
- Uniform Mantle model assumed
- No U/Th in the Core

- Local Geologies Not Considered

Typical Rate
from Crust
30~70 /10^{32}\text{P}/year

from Mantle
~10 /10^{32}\text{P}/year
**Geoneutrino at Kamioka**

Simulated Geoneutrino Origination Points

- **KamLAND**
- Australia
- Greenland
- South America
- Antarctic

*With $10^{32}$ target protons,*
- **U-Series**
  - 32 events / year
- **Th-Series**
  - 8 events / year

*Extensive geology study confined error to <5%,*
- Local characteristic depletion 6~8%
KamLAND Antineutrino Spectrum (expected)

- Japanese reactor operation data provided
- Korean reactor (3.4%) calculated from published electrical output
  ⇒ Total 2% error (conservative)
KamLAND Geoneutrino 1st Result [Nature 436, 499 (2005)]

- Fiducial Volume: 408 ton
- Live-time: 749 days
- Efficiency: 68.7%

Expected Geoneutrinos
- U-Series: 14.9
- Th-Series: 4.0

Backgrounds
- Reactor: 82.3 ± 7.2
- $(\alpha,n)$: 42.4 ± 11.1
- Accidental: 2.38 ± 0.01

BG total: 127.4 ± 13.3

Observed: 152

Number of Geoneutrinos:
$25^{+19}_{-18}$
KamLAND Spectrum Analysis [Nature 436, 499 (2005)]

- Number of Geoneutrinos: \(28.0 \pm 15.6 \)  
- 99% C.L. upper limit: 70.7 events  
- Significance 95.3% (1.99-sigmas)

**Parameters**

\( N_U, N_{Th} \): Number of Geoneutrinos  
\( \sin^2 2\theta, \Delta m^2 \): Neutrino Oscillation  
\( \alpha_1, \alpha_2 \): Backgrounds Uncertainties

- KamLAND is insensitive to U/Th ratio  
  → adopt U/Th \(~3.9\) from Earth science

- **Number of Geoneutrinos**: 28.0 \( \pm 15.6 \)  
- 99% C.L. upper limit: 70.7 events  
- Significance 95.3% (1.99-sigmas)

**Discrimination of U and Th**

\[
\begin{align*}
\frac{(N_U - N_{Th})}{(N_U + N_{Th})} & \quad \text{CL 68.3\%} \\
\frac{(N_U - N_{Th})}{(N_U + N_{Th})} & \quad \text{CL 95.4\%} \\
\frac{(N_U - N_{Th})}{(N_U + N_{Th})} & \quad \text{CL 99.7\%}
\end{align*}
\]
Comparison with Earth Model Predictions

- Consistent with BSE model predictions
- 99%C.L. upper limit too large to be converted to heat production (No Earth models applicable)
Recent Improvements [PRL 100, 221803 (2008)]

- More statistics accumulated: 749 day to 1491 day
- \((\alpha,n)\) error reduced: \(~26\%\) to \(~11\%\)
- Reconstruction improved (off-axis calibration)
- Analysis improved:
  - Fiducial volume increased
  - Time variation included
  - Optimal event selection with figure-of-merit basis
Geophysics with Improved Results

• Error is reduced from 56% to **36%**
• Consistent with BSE model predictions
• **99% C.L. upper limit** is approaching to the total terrestrial heat
KamLAND On-going Effort

LS Distillation in Progress
\[\Rightarrow \text{removes radioactivity by } 10^{-5}\]

we remove these

distilled scintillator
KamLAND Prospects

Assuming:
- $10^{-4}$ reduction of $^{210}$Pb
- Enlarged fiducial volume (5.5m)
- Improved selection criteria
- 749 days livetime

If combined with the current 1491 day data,
- Error is reduced: from 36% to 25% (error is dominated by reactor neutrinos)
- Significance: 99.992% (3.96 sigmas)
Another Good News: Reactors Stopped

- July 2007: Earthquake hit the world largest reactors (Kashiwazaki)
- March 2007: Earthquake hit the closest reactors (Shika)

⇒ ~40% reactor flux reduced
## More Geoneutrino Experiments

<table>
<thead>
<tr>
<th>Project</th>
<th>Location</th>
<th>Mass (kton)</th>
<th>Depth (m.w.e.)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND</td>
<td>Kamioka / Japan</td>
<td>1.0</td>
<td>2700</td>
<td>Running (~7 years)</td>
</tr>
<tr>
<td>Borexino</td>
<td>Gran Sasso / Italy</td>
<td>0.3</td>
<td>3700</td>
<td>Running (~2 years)</td>
</tr>
<tr>
<td>SNO+</td>
<td>Sudbury / Canada</td>
<td>1.0</td>
<td>5400</td>
<td>Soon</td>
</tr>
<tr>
<td>Hanohano</td>
<td>Hawaii / U.S.</td>
<td>&gt;10</td>
<td>~4000</td>
<td>?</td>
</tr>
<tr>
<td>LENA</td>
<td>Somewhere in Europe</td>
<td>50</td>
<td></td>
<td>?</td>
</tr>
<tr>
<td>BNO</td>
<td>Baksan / Russia</td>
<td></td>
<td>4800</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>Homestake / U.S.</td>
<td></td>
<td>4200</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>Kimballton / U.S.</td>
<td></td>
<td>1850</td>
<td>?</td>
</tr>
<tr>
<td></td>
<td>Soudan / U.S.</td>
<td></td>
<td>2070</td>
<td>?</td>
</tr>
</tbody>
</table>
The World Map of Geoneutrino Flux

Typical Rate

from Crust
30~70 /10^{32}P/year

from Mantle
~10 /10^{32}P/year
Reactor Neutrino Backgrounds

World Reactor Locations

Reactor Neutrino Event Rate (1.8MeV < E < 3.3MeV)

KamLAND-II 750 days (expected)

without reactor BG
The World Map of Geoneutrino S/N Ratio

S/N Ratio: (Crust + Mantle) / Reactor

S/N Ratio: Mantle / (Crust + Reactor)
Required Exposure for 20% precision determination

Exposure for 20% precision: \( \text{Sig:}(\text{Crust+Mantle}) / \text{BG:Reactor} \)

- Sensitive to Crustal Composition

Exposure for 20% precision: \( \text{Sig:Mantle} / \text{BG:}(\text{Crust+Reactor}) \)

- Worst Place
- Sensitive to Mantle Composition

Typical Time
- on CC, estimate BSE
  \( 0.5 \sim 1 \ \text{[10^{32}P \cdot year]} \)
- on CC, estimate M
  \( \sim 30 \ \text{[10^{32}P \cdot year]} \)
- on OC, estimate M
  \( 4.5 \ \text{[10^{32}P \cdot year]} \)
Geoneutrino Flux @ Future Detector Sites

S/N Ratio: (Crust + Mantle) / Reactor

KamLAND

SNO+

LENA @ Finland

Borexino

Hanohano

Hawaii (205.00E, 20.00N)
Geoneutrinos: 13.9
(Mantle Origin): 10.4
Reactor Neutrinos: 1.1
KamLAND, Borexino and SNO+: Crustal Neutrino Probing

Different type / age of crusts ⇒ key to understand planetary evolution
Sensitivity (S/N) Comparison

Kamioka (137.31E, 36.42N)
Geoneutrinos: 36.6
(Mantle Origin): 10.3
Reactor Neutrinos: 252.8

GranSasso (14.00E, 42.00N)
Geoneutrinos: 48.5
(Mantle Origin): 10.2
Reactor Neutrinos: 24.5

Time to reach 20% precision
with simple rate analysis
(efficiency / FV fraction NOT considered)

<table>
<thead>
<tr>
<th></th>
<th>Crust</th>
<th>Mantle</th>
</tr>
</thead>
<tbody>
<tr>
<td>KamLAND</td>
<td>12 y</td>
<td>161 y</td>
</tr>
<tr>
<td>Borexino</td>
<td>4.2 y</td>
<td>131 y</td>
</tr>
<tr>
<td>SNO+</td>
<td>1.4 y</td>
<td>96 y</td>
</tr>
</tbody>
</table>
Future 1: Mantle Neutrino Probing (Hanohano)

Hawaii Antineutrino Observatory (Hanohano)

- > 10 kton LS detector
- Mobile, sinkable and retrievable

- 75% from Mantle
- 50% from Lower Mantle
- No Reactor BG
- Simple local geology
Far Future Dreams: Directional Sensitivity

- Mantle under continental crust
- Core / Mantle separation
- Rejection of reactor BG
- Local geology separation
- Earth tomography ??

Recoiled neutron remembers direction

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Problems:
- Thermalization blurs the info
- Gamma diffusion spoils the info
- Reconstruction resolution is too poor

Wish List:
- Large neutron capture cross-section
- (heavy) charged particle emission
  and
- Good resolution detector (~1cm)
LS Directionality and Geoneutrinos

If we achieve
• 20 mm vertex displacement
• 10 mm vertex fluctuation
• Perfect resolution (<~10mm)
Towards Directional Sensitivity

\(^6\text{Li}\) loading helps preserving directional information

- Large neutron capture cross-section: 940 barn
- \(\text{\(^6\text{Li} + n \rightarrow \alpha + T\)}\): no gamma-ray emission
- Natural abundance 7.59%, enrichment possible

\(\text{Li 2.0 wt\% (}\text{\(^6\text{Li} 0.15\text{wt\%})\}}\) Angular Resolution (MC)

\[<\cos\theta> = 0.3608\]
\[\sigma = 0.3782\]

\[<dz> = 17.11 \text{ mm}\]
\[\sigma = 25.07 \text{ mm}\]

LS development at Tohoku U. (under progress)

\(\text{PC + PPO + POE + LiBr + H}_2\text{O} \quad \text{(POE: surfactant)}\)

0.8 wt\% Li,
transparency 65cm@400nm, light yield 45\% KamLAND LS
Towards Directional Sensitivity 2

~1M pixel imaging can achieve 1 cm resolution

- Proper optics need to be implemented
- Sensitivity to 1 p.e. and high-speed readout required

First step for LS imaging...(150cc test bench at Tohoku U.)
Directionality: Current Achievement (Tohoku U.)

- 17 mm vertex displacement
- 20 mm vertex fluctuation
- 10 mm resolution

Li loading:
- 0.8 wt% Li
- Transparency 65 cm @ 400 nm
- Light yield 46% of KamLAND LS

Optics
- 150cc test bench / CCD & II

More info extracted from:
- horizontal distribution
- energy spectrum
- time variation
40K Neutrino Detection

- Emax : 1.31 MeV
  (inverse β minimum: 1.02 MeV)
- Overwhelmed by solar neutrinos
  (inverse β might be only way)

Low $Q_\beta$, low $ft$ isotopes searched...

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Natural Abundance</th>
<th>Ethresh [MeV]</th>
<th>Amount for $\sim 100$ ev/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>187Os</td>
<td>1.6%</td>
<td>1.025</td>
<td>16 Gton</td>
</tr>
<tr>
<td>3He</td>
<td>&lt;0.01%</td>
<td>1.041</td>
<td>7.4 ton</td>
</tr>
<tr>
<td>107Ag</td>
<td>51.8%</td>
<td>1.055</td>
<td>1.7 Gton</td>
</tr>
<tr>
<td>151Eu</td>
<td>47.8%</td>
<td>1.098</td>
<td>680 kton</td>
</tr>
<tr>
<td>93Nb</td>
<td>100%</td>
<td>1.114</td>
<td>6.8 Gton</td>
</tr>
<tr>
<td>171Yb</td>
<td>14.3%</td>
<td>1.119</td>
<td>98 kton</td>
</tr>
<tr>
<td>14N</td>
<td>99.6%</td>
<td>1.179</td>
<td>98 Mton</td>
</tr>
<tr>
<td>79Br</td>
<td>50.7%</td>
<td>1.181</td>
<td>2.1 Gton</td>
</tr>
<tr>
<td>35Cl</td>
<td>75.8%</td>
<td>1.190</td>
<td>4.9 Mton</td>
</tr>
<tr>
<td>135Ba</td>
<td>6.6%</td>
<td>1.227</td>
<td>470 Gton</td>
</tr>
<tr>
<td>155Gd</td>
<td>14.8%</td>
<td>1.268</td>
<td>550 Mton</td>
</tr>
<tr>
<td>33S</td>
<td>0.76%</td>
<td>1.271</td>
<td>14 kton</td>
</tr>
<tr>
<td>106Cd</td>
<td>1.2%</td>
<td>1.216</td>
<td>$\sim 10$ kton</td>
</tr>
</tbody>
</table>


Chen, Neutrino Science 2005
Summary

- Geoneutrinos provide with a **direct measurement of heat producing elements (HPE)**
- Geoneutrinos are **chemical probe to deep Earth**

- KamLAND currently 2σ, 4σ expected in 2y
- Borexino operational (2y), SNO+ soon

- **Future Dreams:**
  - Oceanic Detector / Mobile Detector
  - Multiple Site / Large Detector
  - Directionality
  - $^{40}$K Neutrino Detection
  - ...