Dobrý den

Introduction to Geoneutrinos

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Outline

- Geoneutrinos – what are they?
- Why are they interesting?
- How to detect geoneutrinos?
  - R&D ideas: K-40 geoneutrinos, directionality
- Featuring @ Neutrino Geoscience 2019
  - KamLAND and Borexino new results
  - Future experiments: SNO+, JUNO, Jinping, Baksan
What are Geoneutrinos?

the antineutrinos produced by natural radioactivity in the Earth

Radioactive decay of U, Th, $^{40}$K accounts for >99% of Earth’s radiogenic heat (and a large fraction of the total heat flow)

heat producing elements (HPEs)

Decaying HPEs emit antineutrinos in direct proportion to their heating power

$$\overline{N_{\nu_e}} \rightarrow TW$$

goal: assay the entire Earth by looking at its “neutrino glow”
Uranium, Thorium and Potassium Decay

Table from G. Fiorentini

<table>
<thead>
<tr>
<th>Decay</th>
<th>$T_{1/2}$ [10^9 yr]</th>
<th>$E_{max}$ [MeV]</th>
<th>$Q$ [MeV]</th>
<th>$\varepsilon_D$ [kg^{-1}s^{-1}]</th>
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<tr>
<td>$^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8^4\text{He} + 6e + 6\bar{\nu}$</td>
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<td>$^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6^4\text{He} + 4e + 4\bar{\nu}$</td>
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When neutron-rich heavy elements undergo beta decay, antineutrinos (electron-flavour) are emitted:

$$n \rightarrow p + e^- + \bar{\nu}_e$$
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table from G. Fiorentini

- note: $^{40}$K also has 10.72% EC branch
  - thus also emits neutrinos as well as antineutrinos; but the $\nu_e$ are mostly inconsequential because they have much lower energy, 44 keV (EC to an excited state of $^{40}$Ar, 10.67%) or very small branching ratio, 0.05% to the ground state
Important Questions in Geosciences

what is the radiogenic contribution (U, Th, $^{40}$K) to heat flow and energetics in the deep Earth? – otherwise inaccessible

- mantle: convective Urey ratio?
- geoneutrinos can measure (U and Th for now)
Earth’s surface heat flow \(47 \pm 3\) TW

- Radiogenic heat, mantle: 12-14 TW
- Total radiogenic heat production: 20\(\pm\)3 TW
- Radiogenic heat, crustal: 6-8 TW
- Secular cooling: 18\(\pm\)10 TW
- Tidal dissipation, Chemical differentiation: \(~0.4\) TW

Breakdown of what we think gives rise to the measured heat flow

Figure from Bill McDonough
what is the radiogenic contribution (U, Th, $^{40}$K) to heat flow and energetics in the deep Earth? – otherwise inaccessible

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are the fundamental ideas about Earth’s chemical composition and origin correct?

are the basic models of the composition of the crust correct?
- geoneutrinos can test which ones are
Composition of the Primitive Mantle

Refactories

Mg

Si

Li

Na

K

B

Rb

F

Zn

Lithophile Elements

(abbreviations relative to CI chondrite and Mg-normalized)

Volatility trend @ 1AU from Sun

log 50% condensation Temperature (K) at 10^{-4} atms

slide from Bill McDonough
Silicate Earth Models and Distribution of HPEs

- “Cosmochemical” models
  - EH enstatite chondrite (Javoy et al., 2010)
    - 11-14 TW radiogenic heat
- “Geochemical” models
  - CI chondrite (Rocholl & Jochum, 1993; McDonough & Sun 1995)
    - 17-19 TW radiogenic heat
- “Physical” or “Geodynamical” models
  - energetics of mantle convection (Turcotte & Schubert, 2002)
    - 27-35 TW radiogenic heat

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![Illustrations of layered mantle HPE distributions from “Ferrara group”](image_url)
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- distribution of reservoirs in the mantle?
  - homogeneous or layered?
  - lateral variability

- nature of the core-mantle boundary?

} neutrinos might probe
Expected Rates of Geoneutrinos

1 Terrestrial Neutrino Unit (TNU) = 1 event per $10^{32}$ proton targets per year (assuming 100% efficient detection)

roughly 1 per kilotonne CH$_2$ per year
Mantle Composition
Heterogeneity

Šrámek, McDonough, Learned (2012)

“thermochemical piles” model responsible for lateral variation in the flux (motivated by Large Low Shear Velocity Provinces at the base of the mantle)
Important Questions in Geosciences

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- distribution of reservoirs in the mantle?
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- nature of the core-mantle boundary?

- radiogenic elements in the core?
  - in particular potassium

- what is the planetary K/U ratio? if only we could detect $^{40}$K geoneutrinos…
Volatility trend @ 1AU from Sun
Detecting Geoneutrinos

- inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

Geoneutrino Flux Prediction @ Gran Sasso
(two-layered mantle, “geochemical” model)

![Geoneutrino Flux Prediction](image)

Figure from Borexino 2019 paper
Detecting Geoneutrinos

- inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - “respectable” cross section on protons
  - energy threshold $E > 1.8$ MeV
  - liquid scintillator is $\sim$CH$_2$ hence lots of protons
    - positron makes first scintillation
    - neutron captures on H
      - mean capture time $\sim$0.2 ms
    - delayed 2.2 MeV gamma ray from neutron capture makes second scintillation
  - distinctive signature helps rejects background counts
    - $e^+$ and n correlated in time and in position in the liquid scintillator detector

- figure from Borexino 2019 paper
  - can’t detect $^{40}$K geoneutrinos with this reaction
Detecting Geoneutrinos with Liquid Scintillator

The high quantum yield of the fluor and efficient non-radiative energy transfer result in a high light yield for the scintillator. Charged particles deposit energy (via ionization) in a liquid scintillator. The ionization excites the abundant aromatic molecules of the solvent. These excited molecules transfer their energy to molecules of the fluor, which then deexcite a large fraction of the time (high fluorescence quantum yield) by the emission of photons. The emission wavelengths of the fluor are intended to be longer than that of the solvent; these photons then do not suffer much from absorption by solvent molecules as they propagate through the liquid scintillator. Liquid scintillator cocktails can also have additional components, such as a secondary wavelength shifter. The purpose of the wavelength shifter is to absorb the photons emitted by the fluor and reemit them (with high efficiency) at longer wavelengths that are ideally matched to the spectral response of the light sensors (photomultiplier tubes) being used to detect the scintillation light.

This section has looked at different neutrino detector technologies. There are several techniques that are possible to consider for geoneutrino detection. Radiochemical techniques could also be possible to develop; any approach would have to be specific to the target material desired for the neutrino reaction and the extraction plus quantification of the transmuted atoms that would be produced. Active particle detectors (not radiochemical) collect either the ionization or the light produced by charged particles from the geoneutrino interactions – those being scattered electrons or outgoing positrons from charged-current reactions. A tracking detector such as a TPC could be desirable for detecting geoneutrinos using the antineutrino–electron scattering reaction because of the ability to reconstruct the track direction of the recoil electron. The challenge of constructing a large enough TPC for geoneutrino detection, coupled with the disadvantages of using the electron scattering signal, makes this only a possibility that could warrant investigation.

A scintillation detector was described as being very well suited to detect the positron and the neutron from the inverse beta decay reaction, whereas a water Cherenkov detector was not found to be so. The general design characteristics of a liquid scintillator antineutrino detector were discussed.

15.24.4 Existing and Planned Geoneutrino Detectors

There are two operating geoneutrino detectors in the world: KamLAND in Japan and Borexino in Italy. A third geoneutrino detector is currently under construction, SNO (Gando et al., 2011) in Ontario, Canada. Several other geoneutrino detectors are in the proposal and planning conceptual stage.

15.24.4.1 KamLAND

KamLAND stands for Kamioka Liquid Antineutrino Detector (Gando et al., 2011). It is located in the Mozumi Mine (36.42°N, 137.31°E) under Mount Ikenoyama in the Gifu Prefecture in Japan. KamLAND, like all geoneutrino detectors, is located deep underground in order to reduce backgrounds in the detector from cosmic rays. The amount of rock overburden above the detector is 2700 m water equivalent (the conventional way to describe the depth of underground particle physics experiments).

The detector contains 1000 ton of liquid scintillator composed of 80% dodecane and 20% pseudocumene, with 1.52 g l⁻¹ of 2,5-diphenyloxazole (PPO) added as a fluor. The scintillator volume in KamLAND is contained in a 13 m thin, transparent containment vessel. Array of (1000s) photomultiplier tubes viewing target volume.

Q: can the detection medium be water (H₂O)?

A: in principle, yes; but the Čerenkov process produces much less light than scintillation.

Figure 1 The design or construction of a typical liquid scintillator antineutrino detector.
Neutrino Detection

• to detect (anti)neutrinos, they must first interact to produce a charged particle which can then be observed

• possible targets in ordinary matter:
  • electrons
  • atomic nuclei
    • composed of nucleons (protons and neutrons)
    • composed of quarks

• (anti)neutrinos only undergo the weak interaction

\[
\begin{align*}
\text{CC:} & \quad \bar{\nu}_e + X &\rightarrow e^+ + Y & \quad Y \text{ has } -1 \text{ charge compared to } X \\
\text{NC:} & \quad \bar{\nu}_e + X &\rightarrow \bar{\nu}_e + X' \\
\text{ES:} & \quad \bar{\nu}_e + e^- &\rightarrow \bar{\nu}_e + e^- 
\end{align*}
\]

CC = charged-current weak
NC = neutral-current weak
ES = elastic scattering off electrons
All Possible Geoneutrino Detection Reactions

• NC neutrino-nucleus scattering (coherent)
  • detect the recoiling nucleus, very low energy, many backgrounds

• NC “excitation” of the nucleus
  • incoming neutrino excites the nucleus, then one can detect the gamma rays from nuclear de-excitation

• CC neutrino “absorption” \( \bar{\nu}_e + X \rightarrow e^+ + Y \)
  • detect the outgoing lepton and/or the modified nucleus

• ES neutrino-electron scattering
  • there is directional information – need to exploit – because many backgrounds
Observing the Potassium Geoneutrinos with Liquid Scintillator Cherenkov Neutrino Detectors

Zhe Wang\textsuperscript{a,b,}*, Shaomin Chen\textsuperscript{a,b}

\textsuperscript{a}Department of Engineering Physics, Tsinghua University, Beijing 100084, China
\textsuperscript{b}Center for High Energy Physics, Tsinghua University, Beijing 100084, China

in arXiv:1709.03743 v3
Could a single positron signal be used for $^{40}\text{K}$ geoneutrino detection? What possible nuclear targets? Which one is best? (expanding on MC’s $^{106}\text{Cd}$ idea)

Probing Earth’s potassium content with a new technique for geoneutrino detection
Geoneutrino Projects around the Globe

- **SNO+**: 1 kt, LS+, 5.4 km.w.e. Liquid scintillator filling is in progress!
- **Borexino**: 0.3 kt, LS 3.8 km.w.e. running
- **ANDES**: ~3 kt, LS 4.5 km.w.e. R&D
- **Jinpeng**: 1 kt, LS 7.5 km.w.e. Scheduled
- **KamLAND**: 1 kt, LS 2.7 km.w.e. running
- **JUNO**: 20 kt, LS 1.5 km.w.e. undue construction (2021~)

### Details
- **Ocean Bottom Detector**: 10-50 kt, LS, ~5 km.w.e. movable, R&D
KamLAND 2013 Geoneutrino Published Result

- fixed Th/U ratio 3.9
- $116 \pm 27$ geo $\nu$ events
- oscillated flux $(3.4 \pm 0.8) \times 10^6$ cm$^{-2}$ s$^{-1}$

solid line – model band varies between homogeneous mantle and sunken-layer hypothesis

dashed line – incorporates crustal contribution uncertainty
KamLAND 2016 Prelim Geo $\nu$ Result

Livetime: 1259.8 days 2016 Preliminary Result
model prediction: Enomoto et al. EPSL 288, 147 (2007)

We measured clear distribution of geo-neutrino events!

Data - BG - best-fit reactor $\bar{\nu}_e$
Reference geo $\bar{\nu}_e$
KamLAND data
Best-fit reactor $\bar{\nu}_e$
Accidental
$^{14}C$(α, n)$^{15}$O
Best-fit geo $\bar{\nu}_e$
Best-fit reactor $\bar{\nu}_e$ + BG + best-fit geo $\bar{\nu}_e$

Best-fit: Period 3 analysis

Rate+Shape+time analysis (ratio fixed)

<table>
<thead>
<tr>
<th></th>
<th>[event]</th>
<th>[TNU]</th>
<th>Flux [$\times 10^6$ cm$^{-2}$s$^{-1}$]</th>
<th>0 signal rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>best-fit</td>
<td>model</td>
</tr>
<tr>
<td>U+Th</td>
<td>164$^{+28/-25}$ (17%)</td>
<td>34.9 $^{+6.0/-5.4}$</td>
<td>3.9 $^{+0.7/-0.6}$</td>
<td>4.1</td>
</tr>
</tbody>
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Preliminary

slide from Hiroko Watanabe
Borexino 2015

- 2056 days of data
- $23.7 \pm 6.5 \text{ geo } \nu$ events
Borexino Geoneutrino 2015 Result
Radiogenic Heat

* already favoured a higher value than KamLAND (note: all error bars are large)
Let’s Start the Meeting!