Geoneutrino oscillations approach to discriminate distributions of HPE in the Earth's mantle

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Outline I

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Introduction

- Mantle structure is widely debated.
- Antineutrino detectors are being built.
- There is an exact, relatively simple, way to include an exact solution to the evolution of a neutrino through matter.
- Another way to indirectly probe the deep Earth is then possible.
- This probing can bring information on distribution of HPE distribution as well as heat flux.

Radioactive Decay & Geoneutrinos

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{1}$$

- Alpha $({}^4He^{+2})$
- Gamma $(E_\gamma \sim 100keV)$
- Beta
  - β^+ (e^+, ν_e)
  - β^- $(e^-, \bar{\nu}_e)$
  - Electron capture

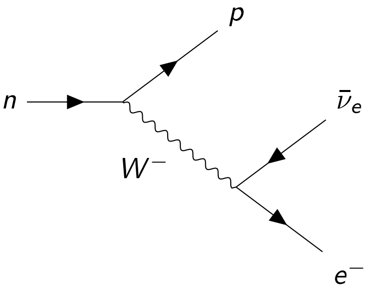

Figure: Feynman diagram for β^- process. This is the process that **generates geoneutrinos**.

Geoneutrinos are **naturally produced** electron antineutrinos (from β^- decay.).

Decay Chains

The isotopes that dominate the geoneutrino production are

$$^{238}U \rightarrow ^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7 MeV, \quad (2)$$

$$^{235}U \rightarrow ^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4 MeV, \quad (3)$$

$$^{232}Th \rightarrow ^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7 MeV, \quad (4)$$

$$^{40}K \rightarrow ^{40}Ca + e^- + \bar{\nu}_e + 1.31 MeV, \quad (5)$$

$$^{40}K + e^- \rightarrow ^{40}Ar + \bar{\nu}_e + 1.505 MeV. \quad (6)$$

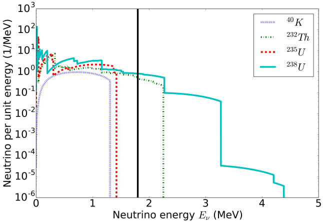

Figure: Geoneutrino energy spectrum from [2].

Bulk Silicate Earth

The Bulk Silicate Earth (BSE) is the combination of silicate parts of the Earth, this is, **crust and mantle**. It's composition has been widely debated [5]. Three main currents have arisen in this matter...

Composition of BSE

- **Geochemical** model is based on geochemical data from peridotites. Reference [6] reports values of: $\boxed{A_{Th}^{BSE} = 79.5\ ppb,\ A_K^{BSE} = 240\ ppm,\ A_U^{BSE} = 20.3\ ppb}$.
- **Geodynamical** model is based on heat flow measurements in the surface. In reference [8], the reported values of the abundances are: $\boxed{A_{Th}^{BSE} = 140 \pm 14\ ppb,\ A_K^{BSE} = 350 \pm 35\ ppm,\ A_U^{BSE} = 35 \pm 4\ ppb}$.
- **Cosmochemical** model is based on the geochemical analysis of enstatite chondrites. Reference [8] reports the following values relevant to this project: $\boxed{A_{Th}^{BSE} = 43 \pm 4\ ppb,\ A_K^{BSE} = 146 \pm 29\ ppm,\ A_U^{BSE} = 12 \pm 2\ ppb}$.

Crustal Abundances

		ρ (g/cm^3)	d (km)	M (10^{21} kg)	Mass		
					U (10^{15} kg)	Th (10^{15} kg)	K, (10^{19} kg)
CC	Sed	2.25[a]	1.5 ± 0.3	0.7 ± 0.1	$1.2^{+0.2}_{-0.2}$	$5.8^{+1.1}_{-1.1}$	$1.3^{+0.2}_{-0.2}$
	UC	2.76	11.6 ± 1.3	6.7 ± 0.8	$18.2^{+4.8}_{-4.3}$	$70.7^{+10.7}_{-10.2}$	$15.6^{+2.3}_{-2.1}$
	MC	2.88	11.4 ± 1.3	6.9 ± 0.9	$6.6^{+4.1}_{-2.5}$	$33.3^{+30.0}_{-15.5}$	$10.4^{+5.7}_{-3.7}$
	LC	3.05	10.0 ± 1.2	6.3 ± 0.7	$1.0^{+0.9}_{-0.4}$	$6.0^{+7.7}_{-3.3}$	$4.1^{+2.2}_{-1.4}$
	LM	3.37	140 ± 71	97 ± 47	$2.9^{+5.4}_{-2.0}$	$14.5^{+29.4}_{-9.4}$	$3.1^{+4.7}_{-1.8}$
OC	Sed	2.03	0.6 ± 0.2	0.3 ± 0.1	$0.6^{+0.2}_{-0.2}$	$2.8^{+0.9}_{-0.9}$	$0.6^{+0.2}_{-0.2}$
	C	2.88	7.4 ± 2.6	6.3 ± 2.2	$0.4^{+0.2}_{-0.2}$	$1.3^{+0.7}_{-0.5}$	$0.4^{+0.2}_{-0.2}$
DM[b]		4.66	2090	3207	25.7	70.6	48.7
EM[c]		5.39	710	704	24.0	113.7	28.7
BSE[d]		4.42	2891	4035	80.7	318.8	113.0

Figure: Values used for calculating the average abundance of U, Th, and K in the Earth's crust. Modified from [4].

The obtained values are $A_U^C = 453.19\ ppb$ and $A_{Th}^C = 1940.64\ ppb$.

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Mantle Abundances

These are calculated according to the mass balance relation

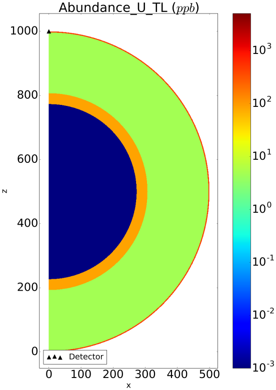
$$m_{BSE} A_X^{BSE} = m_C A_X^C + m_M A_X^M, \tag{7}$$

And the following values are obtained:

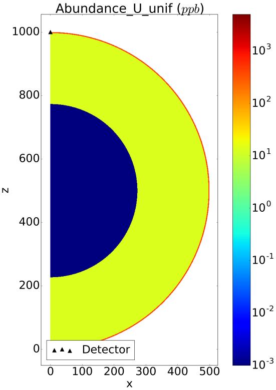
	Cosmochemical	Geochemical	Geodynamical
A_U^M (ppb)	5.14	13.26	28.49
A_{Th}^M (ppb)	13.48	51.06	111.99

Distribution of HPE

I tested two distributions:



(a) Two-layer model. Enriched layer is 10% of mantle's mass.



(b) Uniform model.

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Neutrino Oscillation

- Neutrinos are produced in flavor states $|\nu_\alpha\rangle$: electron ($\alpha = e$), tau ($\alpha = \tau$) or muon ($\alpha = \mu$).
- From QM: Time evolution of a state is given by the hamiltonian $\widehat{H}$.
- Flavor states are **not** energy (mass) eigenstates.
- Flavor states will change while traveling, they will oscillate.
- They travel in a mass eigenstate $|\nu_a\rangle$, $a = 1,\ 2,\ 3$.

- The flavor eigenstates can be expressed as a superposition of the mass eigenstates as:

$$|\nu_\alpha\rangle = \sum_{a=1}^{3} U^*_{\alpha a}|\nu_a\rangle. \tag{8}$$

- **Only the electron flavor** is affected by a potential

$$\mathcal{A} \approx \sqrt{2}G_F\frac{\rho(r)}{m_N}. \tag{9}$$

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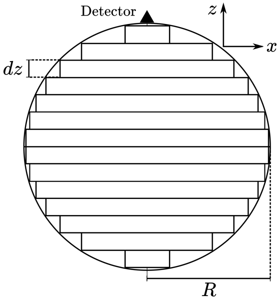
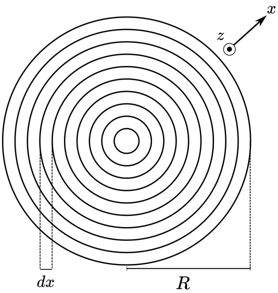
Modeling The Earth I



(c) Cross section of the model-Earth parallel to z-axis.



(d) Cross section of the model-Earth parallel to x-axis (map view).

Figure: The model consists of a 500×1000 matrix in which every element represents a **ring**. For each $z \in [-R, R]$, there are $N(z)$ rings.

Modeling The Earth II

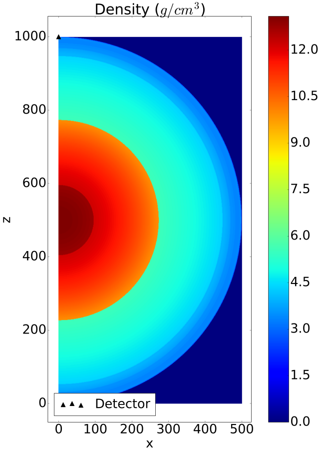


Figure: PREM [1] Model implemented.

Modeling is done in C++.
Each ring has various attributes:

- Coordinates: x, z, r.
- Volume ΔV and Attenuation factor $|\mathbf{r} - \mathbf{r'}|^{-2}$
- Mass density (according to reference [1]), Isotopic abundance.
- Flux contribution.
- A path from each one to the detector.

The Flux Integral I

The flux at a given position **r**, due to HPE at position **r'** is, for isotope X:

$$\Phi_X(\mathbf{r}) = \frac{n_X \lambda_X}{4\pi} \int_\Omega \int_\oplus \frac{a_X(\mathbf{r'})\rho(\mathbf{r'})P_{ee}(\mathbf{r}-\mathbf{r'}, E_\nu)}{|\mathbf{r}-\mathbf{r'}|^2} d^3 r dE_\nu \qquad (10)$$

	^{238}U	^{232}Th
$\mathcal{X}$	0.9927	1
$M\ (u)$	238.051	232.038
$\tau_{1/2}$	4.468	14.05
$\lambda\ (10^{-18}/s)$	4.916	1.563
n	6	4

Table: Values of the different constants in equation 10. Taken from reference [8].

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Survival Probability I

Following reference [7], a program that calculates the survival probability given a **path** and an **energy** was written. It is called **UANdINO**.
The results are comparable with reference those from [7]:

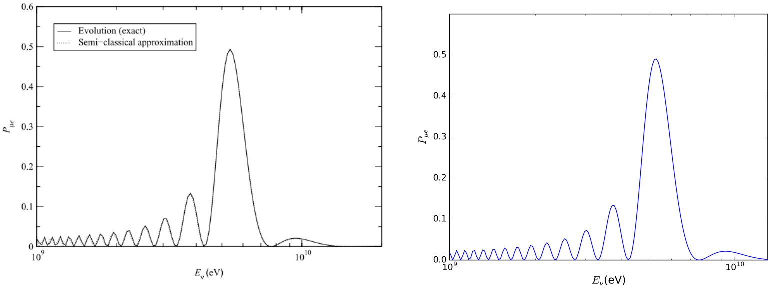

Figure: Left: Transition probability from reference [7]. Right: Plot produced.

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Survival Probability II

In the case of antineutrinos, we get

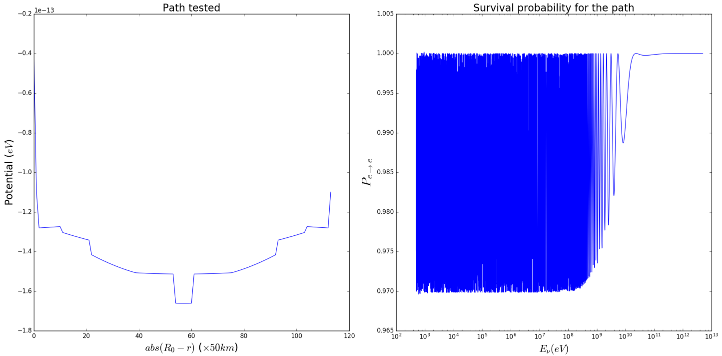

Figure: Antineutrino survival probability for the path shown, which is across the Earth.

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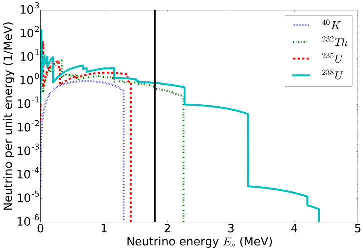
Survival Probability III



- The survival probability is heavily oscillating in the relevant energy domain.
- The probability depends on the spectra, the average should reflect this. **How?**

- Calculate the probability $P(E_\nu)$ for K energy samples within the relevant domain.
- Sample spectrum in the same energies to obtain K f_i's.
- Compute

$$w_i = \frac{f_i}{\sum_i f_i}$$

  the weights for each probability.
- Weight the probabilities to obtain an energy-averaged probability $P(\mathbf{r} - \mathbf{r'})$.
- Do this for each ring.

Survival Probability IV

This results in an average value of

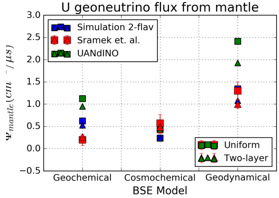
$$\langle P_{ee} \rangle \approx 0.99.$$

But there is an **issue**: Different authors (references [4, 5]) say that the survival probability is well averaged by two-flavor approximation or three-flavor vacuum oscillation formula and that matter effect represents a little contribution to it.

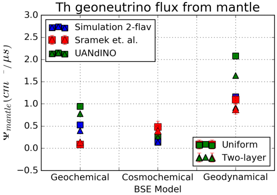
$$\langle P_{ee} \rangle \approx \cos^4 \theta_{13} \left(1 - \frac{1}{2} \sin^2 2\theta_{12}\right) + \sin^4 \theta_{13} \approx 0.54. \tag{11}$$

Mantle's Flux I

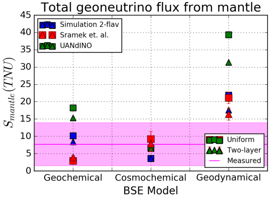
For the three BSE models and both HPE distribution models, the flux was calculated.



(a) *U* flux



(b) *Th* flux



(c) Total geoneutrino mantle signal.

Figure: Simulated geoneutrino signal from the mantle compared to reference [8].

Earth's Flux I

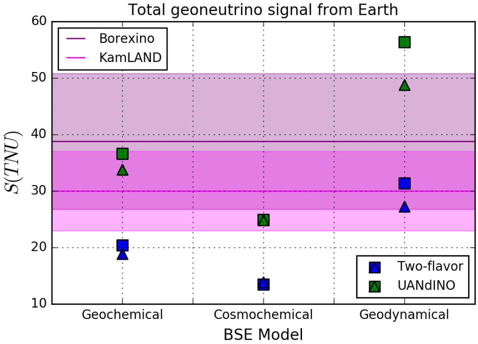
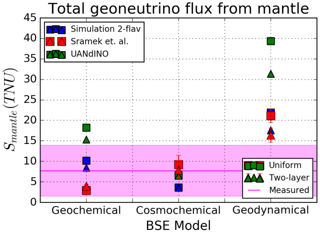
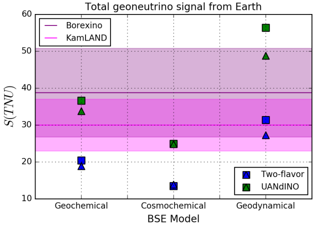


Figure: Total geoneutrino flux expected from the different models. Colored bands correspond to signals measured by the detectors according to reference [5].

Analysis





- UANdINO overestimates mantle flux.
- Nevertheless it gives “good” results for total flux.
- Cosmochemical BSE fits in both situations but does not allow to discriminate HPE distributions
- Geochemical BSE shows fits into total flux and is rather close in mantle flux.
- Two-layer model may be more accurate.

Conclusions I

- Geochemical BSE model seems to be the more accurate.
- The two-layer mantle model gives results closer to the measurements in both, mantle and total, flux.
- The uncertainties in the measurements of neutrino flux, as well as this simulation, are relevant limitations on the study.
- Further work is needed, especially regarding the difference between the survival probability given by the software and the average one given in the literature, and why, despite these quite different probabilities, the results in terms of geoneutrino flux are still reasonable. This involves additional testing to UANdINO to certify the accuracy of the results.

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References I

- Adam M. Dziewonski and Don L. Anderson. "Preliminary reference Earth model". In: *Physics of the Earth and Planetary Interiors* 25.4 (1981), pp. 297–356. ISSN: 00319201. DOI: 10.1016/0031-9201(81)90046-7.
- S. Enomoto. "Neutrino Geophysics and Observation of Geo-Neutrinos at KamLAND". PhD thesis. 2005, p. 233.
- Victor Goldschmidt. *Geochemistry*. 1st ed. The Clarendon Press, 1958.
- Yu Huang et al. "A reference Earth model for the heat-producing elements and associated geoneutrino flux". In: *Geochemistry, Geophysics, Geosystems* 14.6 (2013), pp. 2003–2029. ISSN: 15252027. DOI: 10.1002/ggge.20129. arXiv: 1301.0365.

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References II

- L. Ludhova and S. Zavatarelli. "Studying the earth with geoneutrinos". In: *Advances in High Energy Physics* 2013 (2013). ISSN: 16877357. DOI: 10.1155/2013/425693. arXiv: 1310.3961.
- Shen-Su McDonough, William F; Sun. "The Composition of The Earth". In: *Chemical Geology* 120 (1995), pp. 223–253. ISSN: 00092541. DOI: 10.1016/0009-2541(94)00140-4.
- Tommy Ohlsson and Hakan Snellman. "Neutrino oscillations with three flavors in matter of varying density". In: *The European Physical Journal C* 20.3 (2001), pp. 507–515. ISSN: 1434-6044. DOI: 10.1007/s100520100687. arXiv: 0103252 [hep-ph]. URL: http://arxiv.org/abs/hep-ph/0103252%7B%5C%%7D5Cnhttp://www.springerlink.com/index/10.1007/s100520100687.

References III

- Ondrej Sramek et al. "Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle". In: *Earth and Planetary Science Letters* 361 (2013), pp. 356–366. ISSN: 0012821X. DOI: 10.1016/j.epsl.2012.11.001. arXiv: arXiv:1207.0853v2.
- Edward J. Tarbuck et al. *Ciencias de la tierra una introduccin a la geologa fsica*. 2005, p. 736. ISBN: 8420549983.
- William M. White. *Geochemistry*. ISBN: 9780470656686.