Geoneutrinos: Journey to the Center of the Earth

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Revealing the Invisible with Neutrinos: An Impressionist’s View
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- **solar neutrinos**
  - direct probe of solar energy generation
  - beta decays of fusion products

- **supernova (anti)neutrinos**
  - direct probe of core collapse energy release
  - thermal production

- **geoneutrinos**
  - direct probe of geothermal energy generation
  - beta decays in U & Th chains
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- heat flux measured from thermal gradient
deepest drill core:
\[ \sim 12 \text{ km} = 0.002 \, R_{\text{Earth}} \]
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- net luminosity ~ 40 TW
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    - \( \sim 12 \text{ km} = 0.002 \text{ R}_{\text{Earth}} \)
- anisotropic flux
- net luminosity \( \sim 40 \text{ TW} \)
- energy source?
  - ✓ “primordial” heat
  - ✓ radioactive decays:
    - \( ^{238}\text{U}, \ ^{232}\text{Th}, \ ^{40}\text{K} \)
The Radioactive Earth

- **U, Th** chemically “lithophile”
  - bind to silicates
  - found in crust, not core!
- **K** also in crust, but maybe core?
- Urey ratio

\[
\frac{L_{\oplus,\text{radioactive}}}{L_{\oplus,\text{tot}}} \sim 0.2 - 0.7
\]
Geoneutrino Spectrum

Eder 1966, Krauss et al 1984, Fiorentini et al

- beta decays: antineutrinos $\bar{\nu}_e$
- flux:
  \[\Phi_{\nu, \oplus} \sim \frac{F_{\text{heat}}}{Q}\]
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- Flux: $\Phi_{\nu, \oplus} \sim \frac{F_{\text{heat}}}{Q}$
- Spectral shape: beta decay
- 1.8 MeV inverse beta detection threshold excludes all $^{40}\text{K}$ events, most U & Th events
2005: KamLAND Discovery

- 1 kTon liquid scintillator
  \( \bar{\nu}_e + p \rightarrow n + e^+ \)
- Low-energy signal exceeds reactor flux
- \(~4-54~\) geonu counts (90% CL range)
- Heat flux limit < 60 TW
- Radioactivity an important geothermal energy source!
2010: Borexino Confirmation

- 0.3 kTon liquid scintillator
- geonu detection: $9.9^{+14.6}_{-8.2}$ events (99.73% CL)
- consistent with KamLAND (within large errors)
- georeactor < 3 TW
- combined KamLAND and Borexino: reject no-geo at >5sigma

Fogli et al 2010
Geoneutrino Angular Distribution: Imaging the Earth

BDF & Hochmuth 2006

Future-looking:

imagine directional information

- can resolve geonu image
- intensity $\sim$ sightline column
  \[ I = \int_{los} q \, dl \propto n_{radioactive} \ell \]
- largest emission at largest column
- since most U & Th in crust, signal max at $\sim$ horizon
- image gives 3-D map (tomography) of radioactive earth!
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frontier of antineutrino astronomy

detection solid, but physics murky

linked since Krauss, Galshow, & Schramm 1984

every source precious!

understanding back/foregrounds crucial

large detectors & directional information transformative: open era of nucleo-astro-geo-particle physics
Conclusions

• Geoneutrinos probe radioactive earth and terrestrial energy budget
• Geoneutrinos detected (KamLAND) and confirmed (Borexino)
• Nuclear physics a substantial geothermal power source

Future

• Spectral resolution: separate U, Th inventory
• Directional information: 3-D map of radioactive earth