Geo-neutrino flux calculation

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Abstract. Observation of terrestrial antineutrinos provides information on the origin, composition, and thermal evolution of the earth. Comparing the measured flux of terrestrial antineutrinos with the modeled flux constrains the quantity and distribution of uranium and thorium, the main heat-producing elements within the earth. Because the flux is dominated by nearby crustal material, detailed studies of the local geology are essential to a refined understanding of the bulk earth. This contribution outlines the calculation of the terrestrial antineutrino flux.

1. Introduction
Geo-neutrinos result from the beta decay of terrestrial nuclei. They have maximum energy of a few MeV, allowing them to pass freely through the earth to infrequently interact in large detectors near the surface. A dominant flux of solar neutrinos currently restricts geo-neutrino observations to terrestrial antineutrinos energetic enough to initiate inverse neutron decay. Only four nuclei in the decay series of uranium-238 and thorium-232 produce sufficiently energetic antineutrinos. An initial observation of these antineutrinos agrees with the prediction within the reported measurement uncertainty\textsuperscript{1}. Radiation from these decay series is primarily responsible for the radiogenic heating of the earth. A comparison of rate of heating with the rate of heat flowing from the surface of the earth determines the thermal evolution of the planet. The distribution of heat-producing elements within the earth influences mantle convection, plate tectonics, hot-spot volcanism, and possibly the geo-magnetic field. Geo-neutrino observation remotely senses terrestrial heat-producing elements, enabling novel investigations of the earth’s chemical composition and dynamic processes.

According to earth models, the crust and mantle are the main reservoirs of the principal heat-producing elements, with concentrations greater in continental crust than in mantle and oceanic crust\textsuperscript{2}. This distribution predicts a surface flux of geo-neutrinos significantly higher on continents than in ocean basins, although uncertainties are difficult to quantify\textsuperscript{3}. Moreover, a dominant portion of the continental flux originates from the crust within several hundred kilometers of the detector, making detailed studies of the local geology extremely useful\textsuperscript{4}. As exposure of the two detectors currently recording the interactions of terrestrial antineutrinos accumulates\textsuperscript{1,5}, and construction of a third detector nears completion\textsuperscript{6}, flux modeling becomes increasingly important for constraining proposed distributions of uranium and thorium.
2. Geo-neutrino flux calculation

Geo-neutrino flux is a scalar quantity, diminishing as the inverse square of the distance from the source point to the measuring point. The rate of geo-neutrinos emerging from a source region depends on the concentrations and activities of the parent nuclei. Where the decay of daughter nuclei is involved, secular equilibrium is assumed. Flux calculation is a straightforward integration over all source regions. Assuming radial symmetry the flux contribution $d\phi$ at a surface detector due to a source region at a given radius $r$ and zenith angle $\theta$ is approximately

$$d\phi \propto \rho a r^2 \sin \theta d\theta \left(R^2 - 2rR \cos \theta + r^2\right)^{-1}$$

(1)

where $a$ is the concentration of parent nuclei in the region, $\rho$ is the density of the region, and $R$ is the radius of the earth. The main uncertainty in the flux calculation is the unmeasured concentration of parent nuclei in the inaccessible regions of the deep earth. This is, of course, a principal reason for geo-neutrino studies.

2.1. Mantle

The calculation of the geo-neutrino flux from the mantle assumes radial symmetry, which produces a spatially invariant surface flux. Specification of the physical parameters of the concentric spherical shells follows from seismology. In addition to density, the relevant parameters for each shell include the inner and outer radii. Although uniform in this study, it is a simple matter to vary the concentrations of parent nuclei. The seismic data extend to the center of the earth, allowing for inclusion of the core should models predict appreciable parent nuclei concentrations in this potential reservoir.

2.2. Crust

The predicted geo-neutrino flux from the crust varies significantly over the surface of the earth, being strongly correlated with the thickness of continental crust. A physical description of the crust in two-degree pixels specifies density, thickness, and elevation of seven layers. Of primary importance for calculation of the geo-neutrino flux are the upper, middle, and lower crust layers of 360 possible types. A particular challenge is the assignment of parent nuclei concentrations to these myriad layers.

2.3. Model Earth

An investigation of the dependence of the flux from the mantle and crust as a function of distance from the detector results from a numerical integration over spherically symmetric shells with density and thickness determined by seismology. Integration begins at the core-mantle boundary and extends to a uniform crustal shell at the surface, in which parent nuclei are 125 times more concentrated than in the interior mantle shells. One-half of the flux from the crustal shell originates from source regions within 390 km of the detector. In contrast, one-half of the flux from the mantle shells originates from source regions within 3300 km of the detector. Together these reservoirs form a model earth from which one-half of the flux originates from source regions within 1200 km of the detector. The crustal shell contributes 68% of the total flux in this model. Figure 1 displays the results of these numerical integrations of the geo-neutrino flux without neutrino oscillation effects.

3. Local geology

The results of the numerical integration of the flux from the model earth demonstrate the importance of detailed knowledge of the geology local to the detector. This is particularly relevant to continental locations where the crustal flux dominates. Moreover, predicted parent nuclei concentrations are higher in the upper continental crust than in the less accessible middle and lower continental crust. Geological surveys to determine uranium and thorium concentrations in surface deposits within several hundred kilometers of the location of a continental geo-neutrino detection site are crucial for constraining the quantity and distribution of heat-producing elements within the earth.
Figure 1. The integral, unoscillated flux fraction as a function of distance from the detector for a crust layer (dashed), mantle layers with seismically determined densities (dots), and model earth with crust layer containing parent nuclei concentrations 125 times greater than in the mantle layers (solid). Horizontal line indicates 50% of the integral flux.

4. Conclusions
Calculation of the surface flux of terrestrial antineutrinos is essential for refining understanding of the origin, composition, and thermal evolution of the earth. Comparison of the calculated flux with the measured flux constrains the quantity and distribution of uranium and thorium within the earth. Detailed knowledge of the geology local to the geo-neutrino detection site leads to tighter constraints, especially for continental locations.

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