Geo-neutrino Observation

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Abstract. Observations of geo-neutrinos measure radiogenic heat production within the earth, providing information on the thermal history and dynamic processes of the mantle. Two detectors currently observe geo-neutrinos from underground locations. Other detection projects in various stages of development include a deep ocean observatory. This paper presents the current status of geo-neutrino observation and describes the scientific capabilities of the deep ocean observatory, with emphasis on geology and neutrino physics.

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INTRODUCTION

Geo-neutrinos result from the beta decay of terrestrial nuclei. They have maximum energy of a few MeV. This allows them to pass freely through the earth to interact in large detectors near the surface. A dominant flux of solar neutrinos currently restricts geo-neutrino observations to terrestrial antineutrinos, specifically those from nuclei with β^- decay energy exceeding the threshold for inverse neutron decay. These nuclei are in the decay series of uranium-238 and thorium-232. Terrestrial antineutrino observation relies on detecting both products of this inverse β reaction. The spatial and temporal coincidence of a prompt positron and delayed neutron capture distinctly identifies the interaction of an electron antineutrino. This detection signal measures the antineutrino energy within a few percent in scintillating liquid. Reconstruction of antineutrino direction requires further development of detection techniques. The observation of terrestrial antineutrinos is not without background. Primary sources include cosmic ray muons and reactor antineutrinos. Signal to background improves with increasing overburden and distance from nuclear reactors. Several comprehensive reviews of geo-neutrinos exist in the literature[1,2].

Uranium-238 and thorium-232, the parent nuclei of the decay series producing observable geo-neutrinos, are primarily responsible for the radiogenic heating of earth. Potassium-40 contributes considerably but its β^- decay endpoint energy is below the threshold for initiating inverse neutron decay. Developing the new techniques required to observe geo-neutrinos from potassium-40 would significantly advance the field. The rate of radiogenic heating within the earth compared with the rate of heat flowing

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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[3]. Element concentrations are greater in continental crust than in mantle and oceanic crust. This distribution predicts a surface flux of geo-neutrinos significantly higher on continents than in ocean basins, although uncertainties are difficult to quantify[4]. Without resolution of geo-neutrino direction measuring uranium and thorium concentrations in the terrestrial reservoirs entails observations with both a continental and an oceanic detector[5].

DETECTION PROJECTS

Two detectors currently observe terrestrial antineutrinos from underground locations. Published results are available from the Kamioka Liquid-scintillator Anti-Neutrino Detector (KamLAND) operating since 2002 in a mine in central Japan[6,7]. This detector observes roughly one geo-neutrino event every three weeks, using 1000 tons of scintillating liquid. The measured rate, which carries an uncertainty of 36%, is consistent with a model prediction that fixes the ratio of terrestrial thorium to uranium at 3.9[7]. A primary scientific goal of KamLAND is the measurement of the oscillated spectrum of reactor antineutrinos, of which it detects roughly one event per day. The geo-neutrino observation rate at KamLAND is about 70% of the rate predicted at a continental site. Borexino, a smaller detector operating since mid-2007 at the Laboratori Nazionali del Gran Sasso in a tunnel in Italy, employs 300 tons of scintillating liquid. Its primary scientific goal is the real-time measurement of sub-MeV solar neutrinos[8]. Models estimate a geo-neutrino observation rate of roughly one event every two months at Borexino, about 80% of the rate predicted at a continental site. No antineutrino detection results are available from Borexino at this time.

Other detectors capable of terrestrial antineutrino observation are in various stages of development. The most mature is the next phase of the Solar Neutrino Observatory, called SNO+[9], starting operations as early as 2011 in a deep mine in Ontario, Canada. This location satisfies the requirements for a continental observatory. Other potential continental sites under consideration are in mines in Pyhasalmi, Finland[10] and Lead, South Dakota[11]. A detector in the planning stages endeavors to observe geo-neutrinos from the ocean basin[12]. The design of this deep ocean antineutrino observatory, called Hanohano, allows deployment and recovery at multiple sites of a detector as large as 100 kT[13]. The world ocean, with an average overburden of almost 3800 m.w.e. and large typical distances from nuclear reactors, offers ample deployment sites for geo-neutrino observation with naturally low background. Models estimate the geo-neutrino observation rate in the ocean basins is about 25% of the rate predicted at a continental site. A measurement of the difference in rates at a continental and an oceanic site tests the predicted distribution of uranium and thorium within the earth.

NEUTRINO PHYSICS

The mixing of neutrino mass states diminishes the geo-neutrino flux at the surface of the earth by about 40% with an uncertainty currently much less than the uncertainty in the predicted flux. Because of this disparity in the levels of uncertainty and the dispersed nature of terrestrial uranium and thorium, observation of the geo-neutrino flux contributes little new information on neutrino properties. Geo-neutrino observatories, however, present excellent opportunities for precision measurements of neutrino mixing parameters, including a possibility for resolving the neutrino mass hierarchy. Of particular utility is the movable deep ocean antineutrino observatory.

Deploying Hanohano tens of kilometers offshore a nuclear reactor enables studies of neutrino mixing parameters. Distortion of the reactor antineutrino energy spectrum yields measurements reaching 1% precision with different optimum baselines[14,15]. Energy resolution, which is not critical for measurements of the solar mixing parameters θ_{12} and Δm^2_{21}, is essential for measuring the subdominant mixing parameters θ_{13} and Δm^2_{31}, and resolving the neutrino mass hierarchy. Table 1 lists the observational requirements corresponding to a baseline of 60 km from a 5 GW reactor.

TABLE 1. Exposure requirements for precision measurements of neutrino mixing parameters. Listings for subdominant mixing parameters, mass hierarchy assume energy resolution of $2.5\%E^{1/2}$.

Neutrino Mixing Parameter	Precision	Exposure (kT-yr)
$\sin^2(2\theta_{12})$	1%	24
Δm^2_{21}	1%	60
$\sin^2(2\theta_{13})$	<0.02	76
Δm^2_{31}	1% ($\sin^2(2\theta_{13})$=0.025)	160
Mass Hierarchy	68% C.L. ($\sin^2(2\theta_{13})$=0.025)	80

Note the sensitivity to the subdominant mixing angle parameter $\sin^2 2\theta_{13}$ extends down to 0.02, the value emerging from analyses of global oscillation data[16]. At baselines shorter than 60 km the exposure requirements for the subdominant mixing parameter measurements diminish, while those for the solar mixing parameters increase. Interestingly, a significant source of systematic error in the study of neutrino mixing parameters is the uncertain flux of geo-neutrinos, suggesting observational preference for a more powerful reactor rather than a larger detector.

Monolithic scintillating liquid detectors can achieve the resolution of energy, direction, and charged lepton type required to study the interactions of ~GeV neutrinos from cosmic rays and particle accelerators[17]. This presents an opportunity for exploring the subdominant mixing parameters and for determination of the neutrino mass hierarchy by exposing Hanohano to a high energy muon neutrino beam rather than low energy electron antineutrinos from a nuclear reactor. Comparison of the results from the two methods would constitute a test of CPT conservation.

GEO-REACTOR

Another study benefiting from the movable deployment locations available to an oceanic observatory is the search for a hypothetical geo-reactor. In this search antineutrinos from commercial power reactors are a source of background.

Nonetheless, KamLAND data restrict the power of an earth-centered geo-reactor to less than 6.2 TW at the 90% confidence level[7]. Limits restricting the geo-reactor power to sub-TW levels would result from a relatively brief exposure of Hanohano at a mid-Pacific location[12]. In the event of anomalous flux of reactor antineutrinos observations with Hanohano could discriminate geo-reactor models[18]. With energy resolution enhanced to the level required for the study of subdominant neutrino mixing parameters, measuring spectral distortions specifies the distance to one or more geo-reactors. Multiple observations from widely-spaced deployments resolve the proposed deep-earth locations: earth center, inner core boundary, and core-mantle boundary.

CONCLUSIONS

Observations of geo-neutrinos measure radiogenic heat production within the earth, providing information on the thermal history and dynamic processes of the mantle. Measurements from an oceanic observatory deployed at a mid-Pacific location are ideal for these investigations and for studies of a possible geo-reactor. The same mobile oceanic observatory provides precision measurements of neutrino mixing parameters, including determination of the mass hierarchy, when deployed offshore a nuclear reactor. A deployment intercepting a high energy neutrino beam at an appropriate baseline contributes complimentary measurements. The science capabilities of a large, movable, monolithic scintillating liquid detector are considerable.

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