Oral Presentations

Grand Challenges in solid Earth Sciences

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Recent observations regarding our understanding of the mantle*:*

- The 142Nd controversy no longer exists – the Earth is chondritic
- Collisional erosion models are unnecessary and unfounded
- The radioactive power of the Earth is known to a factor of 3 (10 to 30 TW) and the power left in the mantle is known to within about a factor of 30 (1 to 28 TW).
- Measurements of the planet's geoneutrino flux limit the amount of Th & U in the Earth, defines the building blocks of the planets, and describes convective state of the mantle
- Mg/Si of Earth: solely a function of planetary accretion of olivine to pyroxene. Temperature-time-space variations in accretion disks generate lateral variations in the proportions of olivine(Mg_2SiO_4) to pyroxene($MgSiO_3$) in planets.
- Increased viscosity with depth is consistent stagnation of recycled oceanic lithosphere down to 1000 km depth and with changing shape of ascending plumes at 1000 km depth
- The Earth's ^{182}W isotopic ($t_{1/2}$ = 9 Ma) record reveals core-mantle separation some 30 to 100 Ma after t_0, however, documented ^{182}W isotopic anomalies in the sources of modern to ancient lavas remain.

Challenges we face in understanding the mantle*:*

- The Earth and the Moon are genetically related and, relative to chondrites, both are enriched in refractory elements (e.g., Th & U) and depleted in volatile elements (e.g., K, S, H_2O), with the Moon having a more depleted composition
- The rate of heat loss from the interior of the Earth is known to be between 50 and 150 K/Ga; improvements are needed to better describe the thermal evolution of the planet.
- Compositional attributes of the Transition Zone remain unresolved. Is this region enriched in water? Is this region enriched in basalt (Ringwood & Anderson say yes)?
- Defining precisely and accurately (±few %) modal proportion of olivine in top 650 km of the mantle remains a challenge, doing so will constrain compositional evolution of mantle.
- Defining the mode content (and uncertainties) of ferropericlase (Mg,Fe)O in the lower mantle is required to move beyond speculative models that have transient traction in the literature.
- LLSVP origins is either primordial or subduction related; sources of plume basalts (OIBs) carry a genetic signature of ocean crust recycling and can be traced to LLSVP margins. Xenon isotopes of OIB require 4.4 Ga source evolution difference from Depleted MORB source Mantle. How?
- Stirring efficiency of the mantle remains to be evaluated. Combined chemical, isotopic and geodynamic studies need to model preservations of source heterogeneities.
- Domains of primordial magma ocean differentiates are interpretations of deep Earth seismological features. No geochemical evidence exists to support these interpretations.
- ULVZ domains, parasitically(?) sited on toes of LLSVPs, present an enigmatic feature of CMB that perhaps reflects mass and energy exchange between the core, LLSVP and plunging slabs.

Broad Overview of Neutrino Physics

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Neutrino is an elementary particle attracting physicists' attention. The discovery of the neutrino mass and flavor mixing is a revolution in particle physics, and indicates the existence of the physics beyond the standard model. In the early universe, neutrinos may play a key role to generate matter through a slight imbalance between matter and anti-matter. This theory is based on the hypothesis that neutrinos and anti-neutrinos are identical. The only viable experimental probe for this neutrino nature is the "neutrinoless double-beta decay", which is a special type of undiscovered rare nucleus decay. Many physicists in the world are competitive in the double beta decay search using various types of detectors, aiming at the first discovery of this undiscovered phenomenon. Neutrinos will be essential to reveal the history of the universe.

Geoneutrino flux measurement with Borexino detector

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For the moment Borexino is one of two experiments performed a direct measurement of the geoneutrino flux. The precision of measurement with Borexino achieved ∼25% with the last published set of data and is driven by the statistical uncertainty. The same data excludes the absense of the geoneutrino signal at 5.9σ level and with 98% C.F. confirm the presence of the signal from the mantle. The status of the measurements of the geoneutrino flux with the Borexino experiment and prospects for near future. will be presented.

KamLAND

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The **Kam**ioka **L**iquid-scintillator **A**nti-**N**eutrino **D**etector (KamLAND) is located in a rock cavern in the Kamioka mine, 1,000 m below the summit of Mt. Ikenoyama in Japan. The 2,700 meter water equivalent overburden reduces the cosmic ray flux by a factor of roughly 10^{-5} compared with the surface flux. KamLAND is marked by the ability to detect low-energy antineutrino signals at 1,000 tons of ultra pure liquid scintillator through the inverse β reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. We demonstrated the oscillation nature of neutrino flavor transformation by observing electron antineutrino ($\bar{\nu}_e$) from nuclear reactors and neutrino properties have been explored precisely. Since neutrinos interact with other particles only via weak interaction, they have extremely low reaction probabilities. Such elusive property of neutrinos provides us with the ability to investigate optically invisible deep interior of the astronomical objects, such as the Earth. Neutrino measurement evolved understanding of neutrino properties to utilization of neutrino as a "probe".

The detection of geo-neutrinos, $\bar{\nu}_e$'s produced in β-decays from primordial radioactivities (uranium, thorium, potassium) within the Earth's interior, brings unique and direct information about the Earth's interior and thermal dynamics. KamLAND detects geo $\bar{\nu}_e$ signals above 1.8MeV due to the reaction threshold energy of the inverse β-decay, resulting to have sensitivity to $\bar{\nu}_e$'s from the decay chains of ^{238}U and ^{232}Th. The KamLAND collaboration reported the results of the first study of geo $\bar{\nu}_e$ in 2005 [1]. Later the geo $\bar{\nu}_e$ signals at KamLAND were used to estimate our planet's radiogenic heat production and constrain composition models of the bulk silicate Earth [2]. Following the Fukushima nuclear accident in March 2011, the entire Japanese nuclear reactor industry, which generates >97% of the reactor $\bar{\nu}_e$ flux at KamLAND, has been subjected to a protracted shutdown. This unexpected situation allows us to improve the sensitivity for geo $\bar{\nu}_e$'s [3].

Currently, geo $\bar{\nu}_e$ observed rate is in agreement with the prediction from existing BSE composition models within $\sim 2\sigma$ C.L., but some extreme models start to be disfavored. This ability to discriminate is limited by the experimental uncertainty and crust modeling. In experimental approach, there is a good possibility that recent low-reactor data will provide new insight into geological field. In this presentation, recent results and future prospects of geo $\bar{\nu}_e$ measurement with KamLAND will be presented.

[1] T. Araki et al., Nature 436, 499 (2005)
[2] A. Gando et al., Nature Geosci. 4, 647 (2011)
[3] A. Gando et al., Phye. Rev. D 88, 033001 (2013)

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Geotectonic evolution of the Japanese Islands: an overview

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The geology of Japan recorded nearly 700 million year-long history of a continental margin derived from the Neoproterozoic breakup of the ancient supercontiennt Rodinia. The history of Japan is three-fold; 1) ca. 700-500 Ma (million years ago) as an Atlantic-type margin, 2) 500 Ma to present as a Pacific-type margin, and 3) ca. 50-250 million years after present as a continental collision suture like Himalaya. Around 500 Ma, the margin experienced a large tectonic turnover from the Atlantic-type to the Pacific-type with active subduction, at which a new arc-trench setting appeared to start forming essential orogenic elements; i.e. accretionary complex at trench, high-pressure blueschists along the deeper Wadati-Benioff plane, granitoid batholith beneath volcanic arc, and fore-arc and back-arc basins. The oldest remnants of these orogenic elements in Japan date back to the Cambro-Ordovician time (520-450 Ma), with younger ones of the Siluro-Devonian, Permian, Triasso-Jurassic ages. The occurrence of such full sets of suduction-related orogenic elements guarantees the multiple development of a matured arc-trench system, probably in more or less the same dimension as modern examples, e.g. > 2000 km long and > 200 km wide. Nonetheless, the older remnants are fairly small in total amount, often times occurring sporadically within younger serpentinite mélange zones. In contrast the majority of present surface crust of Japan is composed of Cretaceous and Cenozoic arc granitoids, as shown in recent seismic profiles. These indicate that older pre-existing arc crusts were likely erased from the surface, and replaced by newer arc magmatic rocks. Although granitoids are buoyant material with respect to heavy mantle rocks, older arc granitoids may have subducted/ disappeared into mantle by virtue of mineral phase transition. Large-scale tectonic erosion of granitic crust by subduction, about 5 times of arc crust of modern Japan, is the most promising explanation, of which modern analogue is currently observed off the Pacific NE Japan near Sendai. The putative transportation of granitic crusts in large amounts can generate large-scale heterogeneity in chemical composition, in particular with radiogenic elements, thus in temperature of the Earth's mantle, which can be detected somehow not only by conventional seismological tools but also by the new approach of geo-neutrino research.

References:

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Towards Local Tomography Models with Uncertainties

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High Sensitivity Seismograph Network Japan, Hi-net, was constructed and large amount of data has been accumulated. Although higher resolution tomography models are now available (e.g., Matsubara *et al*. 2008), one of the most significant flaws of previous tomography study is that uncertainties of the obtained model have not been well investigated. The primary reason for this is that uncertainties in both data and *a priori* model (the standard lateral homogeneous model in most cases) are not well known. In this study, we try to evaluate these uncertainties by applying stochastic analysis to the JMA (Japan Meteorological Agency) catalogue data.

Gudmundsson *et al*. (1990) conducted stochastic analysis of global traveltime data and evaluated both random data errors and power spectrum of lateral heterogenieties in the Earth. The former and the latter provide the uncertainties in the data and the *a priori* model, respectively, and they are thus indispensable information to evaluate uncertainties of tomography models. These quantities are obtained by analyzing the coherency of traveltime residuals within bundles of rays of varying size, and similar analysis should be possible to local scale problems. At the time of the presentation, we plan to show the stochastic features of JMA data and hope to show that the amount of uncertainties in the local tomography model in Japan.

References

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Gudmundsson, O., J. H. Davies, & R. W. Clayton, 1990. Stochastic analysis of global traveltime data: mantle heterogeneity and random errors in the ISC data, *Geophys. J. Int.*, **102**, 25-43, doi:10.1111/j.1365-246X.1990.tb00528.x.

Cooling of Earth's core and mantle – With or Without a mysterious structure below the core-mantle boundary

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A mysterious structure below the core-mantle boundary (CMB) region has been found from data analyses on seismological and geomagnetic observations [Helffrich and Kaneshima, 2010; Buffett, 2014]. An interpretation for such a region would be 'stably stratified' caused by either thermal or chemical origin or thermo-chemical origin. Thermal and chemical evolution models of Earth's core have been mainly studied from theoretical approach (the heat flow across the CMB is approximated as simple functional form modeled by mantle dynamics) but not attempted with a coupled core-mantle evolution model in numerical mantle convection simulations. Here we develop the thermo-chemical evolution model of Earth's core and coupled this as a thermal boundary condition for numerical mantle convection simulations.

Without a stably stratified region (pure thermal evolution if Earth's core), the best-fit scenario on thermal evolution of Earth's core would be found with 6000 K of initial temperature at the CMB [e.g. Nakagawa and Tackley, 2010]. With a stably stratified region caused by thermal and chemical effects, the initial temperature at the CMB would not be so high as 6000 K, which is around 4900 K. After rapid cooling caused by huge igneous events in early Earth, the temperature at the CMB seems to be steady state, which is around 3800 K to 4000 K but Earth's core is still cooled down by adiabatic heat transfer across the convective region below the interface of stably stratified region. The cooling process on Earth's deep mantle is somewhat consistent with that inferred from high pressure and temperature measurements on mantle rocks except for magnetic evolution of Earth's core [Andrault et al., 2016]. The thickness of stably stratified region found from this model is around 140 km, which is consistent with an inference from geomagnetic secular variations [Buffett, 2014]. Checking the model sensitivity of heat producing element (HPE) in Earth's mantle, the main scenario on core-mantle evolution would be changed with varying the heat source distribution in the deep mantle.

Conclusions are as follows: 1. The initial core temperature may not be very high but partially molten region in the deep mantle would be still expected. 2. The cooling rate of deep mantle is not very fast if a stably stratified region has been found. A stably stratified region below the CMB might be the strongest heat buffer because not very sensitive to distribution of HPE in the deep mantle.

How can heat flow heat up geoneutrino science?

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Geoneutrino studies aim to investigate the concentration and distribution of the heat producing elements (HPE) uranium, thorium, and potassium inside the Earth. To understand the elusive mantle concentration of these radionuclides it is necessary to subtract from the total measured geoneutrino signal the estimated signal from the HPE enriched lithosphere. Existing studies of the HPE concentration in the crust and lithospheric mantle rely on either extrapolation of geochemical data (from direct sampling and xenoliths) or the relationship between seismic wave speed and bulk composition. Current models assume a spatially homogenous heat production for the upper continental crust, which accounts for half of the heat production of the crust.

There are more than 58,000 heat flow measurements, of which 35,000 have been recorded from the continental crust. The surface heat flux is a function of the Moho heat flux (mantle + core production/residual heat) and crustal production. In stable continental regions (i.e. no tectonic activity for > 1 Ga) we assume a steady state vertical heat flow. Models will be presented that examine the tradeoff between Moho heat flux and crustal heat production.

Geoneutrino studies with JUNO detector

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JUNO is 20 kt liquid scintillator detector under construction at the southern coast of China with a main goal of a precision reactor antineutrino flux studies. The detector will have unique characteristics, providing energy resolution of 3 % at 1 MeV, and among other tasks is suitable for the geoneutrino studies. The potential of the JUNO detector with respect to geoneutrino flux measurements will be presented.

Proposal: Low-energy Neutrino Research at Jinping

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Jinping Neutrino Experiment (Jinping) is a unique observatory for low-energy neutrino physics, astrophysics and geophysics, with 4 kiloton of LS or WbLS. Jinping is located in China JinPing Laboratory (CJPL), identified by the thickest overburden, lowest reactor neutrino background, dominant crustal geo-neutrino signal, lowest environmental radioactivity, etc. In this talk, we will present the strong potential of Jinping towards solar neutrinos, geo-neutrinos and other physics. A number of sensitivity analysis and initial detector R&D studies have been carried, showing Jinping's capacity to measure the transition phase for solar neutrinos oscillation from the vacuum to the matter effect, to discover solar neutrinos from the CNO cycle, and to resolve the high and low metallicity hypotheses with known neutrino oscillation angles, by more than 5 sigma. It has been calculated that Jinping will be able to precisely measure geo-neutrinos with an unambiguous separation on U and Th cascade decays from the dominant crustal anti-electron neutrinos. The estimated event rates of 37 U and 9 Th geo-neutrino events/year/kton will be significantly above the expected ≤ 6 reactor neutrino events/year/kton. The ratio of U/Th can be determined to 10%. We also expect a promising sensitivity for neutrinos from a Milky Way supernova, the diffuse supernova neutrino background, and dark matter annihilation. These physics goals can be fulfilled using mature techniques and the unique opportunity of the CJPL. The first, small phase of the laboratory (CJPL I) is already in operation, hosting dark matter experiments. The second, large phase (CJPL II) is already under construction, with $\approx 100{,}000$ m^3 being excavated.

Future Prospects of Neutrino Oscillation Tomography

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We demonstrate that large neutrino detectors could be used in the near future to significantly improve our understanding of the Earth's inner chemical composition. Matter induced neutrino oscillations depend on the Earth's electron density, while seismic measurements are sensitive to the matter density. The Earth's chemical composition can be determined by combining observations from large neutrino detectors with seismic measurements. We present a method that will allow us to distinguish between composition models of the outer core. We show that the next-generation large-volume neutrino detectors already provide sufficient sensitivity to reject extreme cases of outer core composition. The prospect of neutrino oscillation tomography will be discussed in the context of the PINGU (Precision IceCube Next Generation Upgrade).

Towards a refined model for predicting geoneutrino signal at SNO+

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The SNO+ detector is foreseen to observe almost in equal proportion electron antineutrinos produced by U and Th in the Earth and by nuclear reactors. The prediction of the geoneutrino signal at SNO+ is based on the modeling of the distribution and amount of U and Th in the Earth's reservoirs and can be subtracted from the experimentally determined total geoneutrino signal to estimate the mantle contribution. I will present the 3-D refined geological model of the main reservoirs of U and Th in the regional crust extended for approximately 2×105 km2 around SNOLAB, including estimates of the volumes and masses of Upper, Middle and Lower crust, together with their uncertainties. According to a global reference model this portion of the crust contributes for 43% of the total expected signal at SNO+. The remaining contributions come from the far field crust (34%), from continental lithospheric mantle (5%) and from the mantle (18%).

The main crustal reservoirs are modeled by identifying three main surfaces: the Moho discontinuity, the top of the Lower Crust and the top of the Middle Crust. About 400 depth-controlling data points obtained from deep crustal refraction surveys and from teleseismic receivers are the inputs for the spatial interpolation performed with the Ordinary Kriging estimator. The numerical 3D model consists of about 9 × 107 cells characterized by geophysical information and U and Th content. The total geoneutrino signal at SNO+, expressed in Terrestrial Neutrino Unit (TNU), is 40+6-4 TNU, approximately 12% less than that calculated using the global reference model.

The Huronian Supergroup-Sudbury Basin (HS-SB) unit is the strongest geoneutrino source among the local crust reservoirs and it is predicted to produce 7.3+5.0-3.0 TNU. The compositional heterogeneity of this lithologic unit affects the geoneutrino signal uncertainty on the order of 60%. A systematic sampling of the main lithologies of the HS-SB for improving the knowledge of the U and Th content of the unit and a more stringent constraint on the local contribution to the geoneutrino signal are the goals of the current studies.

Revealing the Earth's mantle from the tallest mountains using the Jinping Neutrino Experiment

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The Earth's engine is driven by unknown proportions of primordial energy and heat produced in radioactive decay. Unfortunately, competing models of Earth's composition reveal an order of magnitude uncertainty in the amount of radiogenic power driving mantle dynamics. Comparison of the flux measured at large underground neutrino experiments with geologically informed predictions of geoneutrino emission from the crust provide the critical test needed to define the mantle's radiogenic power.

We predict the geoneutrino flux at the site of the Jinping Neutrino Experiment (Sichuan, China). Within 8 years, the combination of existing data and measurements from soon to come experiments, including Jinping, will exclude end-member models at the 1σ level, define the mantle's radiogenic contribution to the surface heat loss, set limits on the composition of the silicate Earth, and provide significant parameter bounds for models defining the mode of mantle convection. We sketch how the geoneutrino measurements at the three relatively near-lying ($\lesssim 3000\,\mathrm{km}$) detectors KamLAND, JUNO, and Jinping may be harnessed to improve the regional crustal models.

New vision of water in the Moon

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Lunar water is one of the most important subject to understand the Moon-Earth system. A post-Apollo view called for a dry Moon from the surface to the interior (<1 ppb), in direct contrast with the Earth. Considering this dry Moon scenario, formation and evolution processes have been modeled up to now; A high-energy Giant impact, high-temperature lunar magma ocean and loss of volatiles by volcanic eruption can be supported by water-depleted past to present Moon.

With the discoveries of water-rich accessory minerals in the Apollo samples, questions concerning water in the Moon have recently been revived. Furthermore, most recent our investigations found mantle-originated water in the constitute minerals of olivine, pyroxene and plagioclase in gabbroic lunar meteorites. Water contents of these minerals proposed a wet mantle view based on the inferred mantle water content up to 409 ppm with several assumptions. This wet Moon scenario proposes new visions into the Moon’s history, e.g., accumulation of cold and volatile-rich fragment after low-energy Giant Impact, partial melting of water, KREEP and Th-rich mantle by the overturn and a cause of deep moonquakes. Since the Apollo era, there remains such unresolved but important problem concerning lunar water: conflicting hypotheses between the dry and wet Moon scenarios”. Neutrino physics promises a new insight into this problem because it is useful tool to understand thermal and compositional information on the lunar interior that is closely related to evolutionary history of water in the Moon-Earth system.

Robust Geo-neutrino Results

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Geo-neutrino observations uniquely probe the quantities and distributions of the terrestrial heat-producing elements- uranium, thorium, and potassium. The quantities of these elements gauge planetary radiogenic power, offering insights into the origin and thermal history of the Earth. The distributions reveal the initial partitioning and subsequent recycling of these elements between metallic core, silicate mantle, and crust types. Ongoing observations at underground sites in Japan and Italy record the interactions of geo-neutrinos from uranium and thorium but not from potassium. Most reports of the geo-neutrino rates observed at the sites assume a spectral shape given by the ratio of thorium to uranium masses found in chondritic meteorites. This assumption allows biased assessments of the fluxes of geo-neutrinos from uranium and thorium. The most recently reported fluxes measured at the two underground sites are consistent within experimental uncertainties. They support equally well both uniform and non-uniform concentrations of uranium and thorium within the Earth. Analyses of the measured fluxes separate a mantle signal from a crust signal, which is predicted by geological modeling. This separation allows estimates of radiogenic heat production for assumed mantle distributions. Opportunities for measuring non-uniform distributions of heat-producing elements and for estimating radiogenic heat production by methods that are free of assumptions of spectral shape and geological modeling await future observations of geo-neutrinos. Observations at geologically contrasting sites, such as the Himalayas and the middle of the Pacific Ocean, facilitate these robust geo-neutrino results.

Poster Presentations

Performance Evaluation of Mirror for Imaging Detector

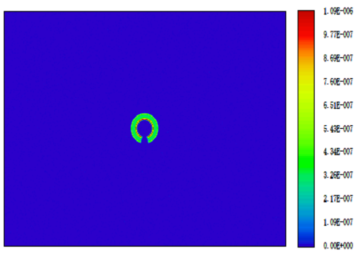
RCNS, Tohoku Univ

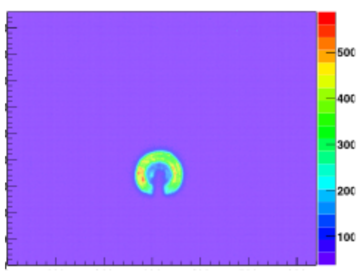
K.Soma, K.Inoue, T.Mitsui, H.Watanabe, K.Ishidoshiro, Y.Shirahata, T.Takai

This lecture is about performance evaluation of imaging detector for directional measurement of electron anti-neutrino. “Imaging detector” is a detector that combines optics and photon detector, thanks to this, we can get high resolution. There are many kinds of optics, we use a mirror as a part of imaging detector.

In detecting prompt signal and delayed signal, we can observe anti-neutrino events in liquid scintillator. However, we can’t get directional information. To get directional information, we must separate two points, reaction-point of the prompt signal and absorption-point of the delayed signal, and observe it. It needs a detector that the aberration is under about 40mm for separation of these points. The aberration is about 100mm in using only Photomultiplier Tube(PMT). So we develop imaging detector that have a high resolution and try to resolve this aberration problem.

In this experiment, we designed a mirror by simulation. While changing length from mirror to LED, we observed light condensing with CCD camera. Picture 1 is a sample of some images. Left side is simulation , another side is observation. By analyzing these images, we compared observation and simulation and evaluation performance of mirror.





Picture 1. Sample of some images, simulation(Left) and obsevation(Right)

Study of Particle ID
in Liquid Scintillator using Imaging Detector

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Liquid scintillator (LS) detectors have a good sensitivity to low energy anti-neutrinos. On the other hand, unlike water Cherenkov detectors, LS detectors are not sensitive to direction of anti-neutrinos. Directional sensitive LS detector has rich potential. For example, it will contribute to the better understanding of the Earth’s interior using geo-neutrino flux measurement in kton scale detector, and there is a possibility of application to reactor monitoring system in small size detectors.

Anti-neutrinos are detected by inverse beta decay reaction and tagged by the delayed coincidence method (prompt signal is a positron event and delayed signal is a neutron capture event) that provides a powerful tool to reduce backgrounds. Although the emitted neutron retains the directional information of the incoming anti-neutrino, current LS cannot identify the neutron capture point before it loses the information. Li-loaded LS has the ability to shorten the neutron capture range because of large neutron capture cross section (940barn cf. ^{1}H 0.3 barn) of ^{6}Li. To separate prompt and delayed points clearly, the optical discrimination of energy deposit point by high resolution imaging devices is also required. Design of imaging device is a combination of optics and PMTs.

Prototype of imaging device was made and evaluated. We propose to apply it to particle identification which can also enhance the background reduction. High resolution provided by imaging device makes particle identification available. Experimental study of identification of beta ray and gamma ray will be reported.

A Web Application for Modeling Anti-Neutrino Emissions

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We present a web application with interactive tools to quickly visualize models of anti-neutrino emissions from both the Earth and nuclear reactors. The application allows numerous user inputs, facilitates analyses of signals, and provides near instantaneous results. Results include 'heat map' visualizations, anti-neutrino event spectra, and radiogenic power constraint validation, amongst others. We exhibit the features of the web application in a live demo: https://geoneutrinos.org/. Participants are invited to bring their laptop and follow along.

Abstract for International Workshop on Neutrino Research and Thermal Evolution of the Earth

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Understanding the inner structure and composition of the Earth is fundamental to Earth science. Even though Earth's density is known very well, the chemical composition of the Earth's core has not yet been measured. Neutrinos, which are naturally produced in the atmosphere, traverse the Earth and undergo oscillations that depend on the Earth’s electron density. Using neutrino oscillations we can remotely measure the electron density of Earth's core and hereby determine chemical composition of the Earth's core.