

Detection of Geoneutrinos: Can We Make the Gnus Work for Us?

John G. Learned

Department of Physics and Astronomy, University of Hawaii,
2505 Correa Rad, Honolulu, HI 96822 USA

E-mail: jg1@phys.hawaii.edu

Abstract.

The detection of electron anti-neutrinos from natural radioactivity in the earth has been a goal of neutrino researchers for about half a century[21, 22, 23, 24, 25, 26]. It was accomplished by the KamLAND Collaboration in 2005[27], and opens the way towards studies of the Earth's radioactive content, with very important implications for geology. New detectors are operating (KamLAND[3] and Borexino[2]), building (SNO+[4]) and being proposed (Hanohano, LENA, Earth and others) that will go beyond the initial observation and allow interesting geophysical and geochemical research, in a means not otherwise possible. Herein we describe the approaches being taken (large liquid scintillation instruments), the experimental and technical challenges (optical detectors, directionality), and prospects for growth of this field. There is related spinoff in particle physics (neutrino oscillations and hierarchy determination), astrophysics (solar neutrinos, supernovae, exotica), and in the practical matter of remote monitoring of nuclear reactors.

1. Introduction: Geoneutrino Studies Started

The preceding paper, "Why Geoneutrinos are Interesting"[1], really sets the stage for this contribution to NU2008. McDonough explains that the flux of geoneutrinos coming mainly from the natural radioactive decay chains of Uranium and Thorium from throughout the earth, serves as a tag for the abundance and location of these rare isotopes. While much of this radioactive material is surely in the relatively thin continental crusts, roughly one half resides in the mantle. Quite surprisingly to many physicists, these most detectable of the natural decay neutrinos are thought to originate in the decay chains that constitute the major source of the Earth's internal heating. That heating in (or under) the mantle of course is responsible for all of the mantle circulation which produces continental drift, seafloor spreading, mid-ocean volcanoes and traveling hot spots, and of course earthquakes and tsunamis. Moreover, the geomagnetic field is thought to be produced in the outer core of the earth, which is liquid (as we know from the lack of seismic shear waves), largely composed of Iron and Nickel, and which convects much faster than the viscous mantle material (mostly silicates). There is not much certain about the depth and configuration of the mantle convection, nor of the lateral homogeneity of the U/Th abundances. Moreover, there is no consensus about the exact magnetohydrodynamical processes in operation to produce the geomagnetic fields, which do indeed change significantly on a human timescale though having been present for billions of years.

In principle one can perform a kind of tomography with neutrinos to map out the distribution of the sources. The job is however a tough one, being that thousand ton scale detectors (e.g. KamLAND) are required to even begin first detection measurements. Moreover the high sensitivity required demands employment of expensive liquid scintillators in order to produce significant light (yielding 30-50 times that from a Cherenkov detector) and further, almost all neutrino directionality is lost. Further, delicate care must be taken for radiopurity, now well understood but not easy.

The process employed for detection of the anti-neutrinos is the inverse beta decay, used by researchers since the initial observations of these neutrinos by Cowan and Reines in the 1950's. The signature consists of two flashes of light, near in time and space, and of similar amplitude. The first flash is due to the annihilation of the positron which results from a (free) proton being struck by an electron-antineutrino (one can think of it as the neutrino stealing a charge from the proton). The neutron is then free to wander about until it captures on another proton to form Deuterium, with the liberation of the 2.2 MeV binding energy. The primary interaction has a threshold of the proton-neutron mass difference, and is 1.3 MeV. Hence the key geonu signature is the detection of a primary flash equivalent to a neutrino energy between roughly 1.3 and 3.6 MeV (and consisting of a thousand or so photons), a second flash equivalent to 2.2 MeV and delayed by about 200 microseconds, and everything originating in a region on the order of one meter in size in the detector. This forms a beautiful discriminant against non-anti-neutrino backgrounds of order 10^9 (depending on size, depth and other factors, including rejection of solar neutrinos which make only one flash).

2. Various Experiments

The following table indicates the operating, soon to be operating, and proposed experiments of relevance around the world. KamLAND has been operating for 6 years now, and is described in the talk of Decowski[3]. It was the first to report detection of neutrinos from the earth, as was done in a cover article in Nature in 2005[27]. This detection, now improved since publication, presented the first demonstration of the expected signal from terrestrial radioactivity and, though feeble in statistical power, is roughly in agreement with expectations (to order 20%).

Unfortunately measurements on the continental crust will mostly measure only those neutrinos originating in the crust in the detector's neighborhood (500 km or so), with the mantle originating neutrinos only contributing on the order of 25% to the total. Since even the predictions of the local crustal neutrino flux are uncertain at the 20% level, one cannot discern the mantle contribution from a detector location on or near the continental plates. Nonetheless, measurements of the geoneutrino flux from continental locations are interesting, since neither the total amount of the U & Th in the Earth is certain, nor is the distribution between crust and mantle.

The Borexino detector in a tunnel of the Gran Sasso Laboratory in the Apennines in Italy has started in 2007 and has solar neutrino data already[2], but at 100 tons mass is too small to make much contribution to the geoneutrino business.

The SNO+ detector[4], as a 1000 ton liquid scintillator conversion of the older SNO (heavy water) detector in Subury Canada, will make interesting crustal measurements in a location above ancient continental plate.

The LENA detector[8] has been talked about for a few years in Europe as a very large, mine based, liquid scintillator detector in the 50-100 kiloton class. It is now part of the trio of detectors being studied as a European Megaproject (MEMPHYS, along with a megaton water Cherenkov instrument, Laguna, and a 100 kiloton liquid argon device, Glacier). Various locations have been suggested but the favorite for LENA appears to be in a mine in Pyhalsalmi, Finland. The LENA team is centered in Munich, and they have done many excellent studies of the physics and technology for this proposed project. An option to place LENA underwater co-located with

the NESTOR Project near Pylos, Greece has been discussed, but appears not to be the main plan at this time.

The EARTH project has been presented by a Dutch/South African team, with the goal of putting a many-armed detector underground on the Island of Curacao[9]. The notion is to employ long, relatively thin, layered neutrino detectors, getting some directionality from the relative rates in each arm. A detailed detector design has not been presented yet, and performance is as yet not well determined.

Table 1. `jpconf.cls` List of various geoneutrino experiments.

Detector	Region	Location	Size	Status (Start)
KamLAND	Japan	Mine	1000 T	Operating (2002)
Borexino	Italy	Tunnel	100 T	Operating (2007)
SNO+	Canada	Mine	1000 T	Construction (2010)
Hanohano	Pacific	Ocean	10,000 T	Proposed (2013?)
LENA	Finland?	Mine	50,000 T	Proposed (?)
EARTH	Curacao	Drill Holes	??	Discussed (??)

3. Hanohano

A deep ocean antineutrino observatory called Hanohano (Hawaii Anti-Neutrino Observatory) is being developed at Hawaii and with collaborators elsewhere[10]. The observatory will record interactions of electron antineutrinos of $E_\nu > 1.8MeV$ by inverse β -decay in a monolithic cylindrical detector of 10 kt of ultra-pure scintillating liquid. An outer surface array of inward-looking 10-inch photomultiplier tubes in 13-inch glass pressure housings will collect scintillation photons. The planned energy resolution is $3.5\%/\sqrt{E_{vis}}$, with $E_{vis} = E_\nu - 0.8MeV$ the visible energy. Sufficient overburden (3 km or more for most sensitive geonu studies), adequate shielding (from ocean radioactivity), and radio-pure detector components will limit background to negligible levels providing very high detection efficiency.

Considerable science potential derives from the ability to deploy the observatory at various deep ocean locations. An initial deployment offshore a nuclear reactor complex for measuring neutrino mixing parameters could be followed, for example, by a deployment near Hawaii for measuring terrestrial antineutrinos. This flexibility presents a significant advantage over similar observatories at a fixed underground locations.

The preliminary design, resulting from a two year engineering study by Makai Ocean Engineering, specifies the detector to be a right cylindrical shape, transported in a special barge from which it may be deployed, and recovered. The inner volume of liquid scintillator is separated from the photodetectors by a segmented acrylic layer. The individual optical units are in clusters, in plain oil. Outside this stainless steel vessel will be a further layer of 2 meters of pure water, and veto photomultipliers (as well this layer provides access to the inner tank for installation and repairs). Very importantly in this design, all fiber-optic and electrical connections will be made pier-side, tested and calibrated prior to deployment (avoiding previous bad experience with unreliable connectors in the ocean, and difficult remote connections via robot). The detector design is aimed at multiple deployments on a roughly annual cycle, allowing changes of venue to follow the science.

3.1. Hanohano Geoneutrino Studies

The Hanohano team aims for measuring the flux of U/Th geo-neutrinos from earth's mantle with 25% uncertainty in one year of operation near Hawaii[28]. Included in this statistic-dominated result is 9% systematic error due to uncertainty in the U/Th content of the crusts. This same uncertainty limits the precision of measurements of the mantle flux at continental locations to $> 50\%$. Not included in the analysis is uncertainty of the neutrino mixing angles θ_{12} [3] and θ_{13} [30]. The survival probability for fully mixed geo-neutrinos is 59% (+6%, - 15%), as measured at present. The upper (lower) value obtains with minimum (maximum) present values of the mixing angles. Imprecise knowledge of mixing angles and U/Th content of earth's crusts introduce comparable uncertainties to the measurement by Hanohano of geo-neutrinos from the mantle. Nonetheless, deployments at several widely-spaced mid-ocean locations test lateral heterogeneity of uranium and thorium in the mantle.

Geo-neutrinos with energy between 1.8 MeV and 2.3 MeV come from both ^{238}U and ^{232}Th decay products, while those between 2.3 MeV and the maximum energy of 3.3 MeV are only from the ^{238}U decay product ^{214}Bi . This spectral feature allows a measurement of the Th/U ratio. Although geology traditionally ascribes the chondritic Th/U ratio of 3.9 ± 0.1 to the bulk earth, samples from the upper mantle reveal a substantially lower value of 2.6 suggesting layered mantle convection[31]. Geo-neutrino flux measurements sample large volumes of the deep earth providing an important test of mantle convection models.

An earth-centered natural fission reactor[32, 33] is a speculative, untested hypothesis. Predicted to be in the power range of 1-10 TW, it has the potential to explain the variability of the geo-magnetic field and the anomalously high helium-3 concentrations in hot-spot lavas. Fission products from such a geo-reactor would undergo β -decay, producing antineutrinos with the characteristic nuclear reactor spectrum. A one-year deployment of Hanohano at a mid-ocean location well distant from nuclear power plants tests the existence of the geo-reactor. This deployment would set a 99% CL upper limit to the geo-reactor power at 0.3 TW or, were a 1 TW geo-reactor to exist, produce nearly a 5σ measurement[29].

3.2. Hanohano Neutrino Studies

Neutrino mixing and oscillation[11] are responsible for the deficit of solar neutrinos[12], the spectral distortion of reactor antineutrinos[13], and the deficit of atmospheric muon neutrinos[14], which has been confirmed using an accelerator-produced muon neutrino beam[15]. These initial observations reduce the allowed regions of neutrino mixing parameter space, guiding future precision measurements of mixing angles and mass-squared differences, including resolution of the spectrum of neutrino masses. Positioning Hanohano 60 km distant from a nuclear reactor complex enables precision measurement of θ_{12} and, for non-zero θ_{13} , δm^2_{31} . This latter measurement can lead to a determination of neutrino mass hierarchy.

Several authors discuss a precision measurement of the solar mixing angle θ_{12} using antineutrinos from a nuclear reactor[16, 17, 18]. The experiment utilizes a near detector at the reactor complex for normalizing flux and cross section with a far detector at the first minimum of survival probability. There is agreement that an exposure of 60 GW-kt-y of a far detector at a distance of 60 km yields an uncertainty of 2% in the value of $\sin^2(\theta_{12})$ at the 68% confidence level, assuming a detector systematic uncertainty of 4% or less. This experiment is analogous to methods proposed for precision measurement of the sub-dominant mixing angle θ_{13} [19], namely the reactor antineutrino flux sampling defines one-half cycle of the oscillating survival probability. The difference is the distance of the first minimum of survival probability, which is 2 km for the θ_{13} measurement.

The far detector for the θ_{12} experiment records multiple cycles of δm^2_{13} oscillation given that $\theta_{13} > 0$, the detector has adequate energy resolution, and sufficient exposure. There is a plan to measure these cycles in L/E space by sampling the Fourier power at different values

of δm^2 [20]. This self-normalizing, robust method offers a precision measurement of δm^2_{13} for $\sin^2(2\theta_{13}) > 0.05$, determines neutrino mass hierarchy by evaluating asymmetry of the Fourier power spectrum, and measures θ_{13} ; all without the need for a near detector.

Hanohano is capable of performing the experiments described above with a one-year deployment offshore a suitable nuclear reactor complex. At least two candidate sites with considerable overburden exist. One is in 1100 m of water West of the 7 GW San Onofre reactors in California and the other is in 2800 m of water east of the 6 GW Maanshan reactors in Taiwan. Other locations are possible.

3.3. Hanohano Other Physics Opportunities

The existence of a detector with the capabilities of Hanohano and the location deep inside the ocean offers an opportunity for several exciting discoveries. Here we indicate some of them briefly. One is a search for an anti-neutrino signal from relic supernovae from the distant past. The signal can be as large as 4 events per year[34]. Of course, the signal from a galactic supernova is much more robust: about 2000 conventional anti-electron neutrino capture events, with additional charged current events from ^{12}N , ^{12}B , and neutral current events from scattering on electrons and ^{12}C . There are also about 2000 events of elastic scattering on protons. This would be a signal in addition and complimentary to those from all other detectors around the world.

If the purity levels in the scintillating liquid can be made as low as in Borexino, then one may search for the neutrino signal from solar neutrinos especially the pep line and the CNO neutrinos. The signal from pep+CNO in the window of 0.8 to 1.3 MeV is expected to be about 150 events/day/10kt. This is detectable against an expected background of about 130 events/day/10kt, mostly from ^{11}C . This is very useful in confirming the conventionally accepted neutrino parameters and to rule out some non-standard neutrino properties[35].

Finally, Hanohano has the capability to detect the proton decay mode $p \rightarrow \nu + K^+$. This is expected to occur in super-symmetric models. Liquid scintillation detectors an advantage over conventional water-Cherenkov detectors by being able to detect the kaon directly. Hanohano can reach a sensitivity of almost 10^{34} y.

4. The Sad Story of K40 Detection

Geologists would very much like to detect the neutrinos from Potassium-40 decay[1]. This common isotope has different chemical properties than the heavy elements, and is thus to be found in different regions of the Earth, from the oceans and crust to the core. The unfortunate case is that the end point energy (1.3 MeV) is below the inverse β threshold, and hence the signature of these neutrinos' interactions is only one flash of light, to be extracted from the solar neutrino and other backgrounds. We will not say more here, other than to report it as a major challenge for which good ideas are needed[24].

5. Towards Directionality

A great challenge for a next generation of low energy anti-neutrino detectors is achieving some directional resolution. People have discussed tracking detectors, but the sizes required are formidable and not yet practical. The nearest opportunity seems to be with the inverse- β decay itself. The neutron acquires a tiny (few keV/c) amount of momentum from the striking neutrino. If one can record the positron appearance location and the neutron absorption location, one can make a poor ($O(20^\circ)$) angular determination. Improvements in present technology can come through better vertex resolution, track resolution, shorter scintillator emission times, heavier materials (shorter gamma travel distances), and greater neutron cross sections. Employment of an alpha emitter can help in locating the neutron absorption, but the alpha's suffer from greatly decreased light yield due to saturation of the scintillator by heavily ionizing particles.

Imaging can help by permitting one to recognize the annihilation gamma's topology and getting a better initial neutrino interaction vertex. Ditto for the neutron absorption location. Advances in CCDs and optics may make some significant progress here, but not immediately. Studies are underway at several institutions (particularly at RCNS, Tohoku) to push ahead in this area.

6. Other Applications

Due to lack of space we cannot elaborate upon the practical applications of these detectors. An introduction is given in Bowden[7], where the focus is upon close-in reactor monitoring. Remote monitoring of reactor activity will be possible out to hundreds of kilometers with next generation instruments, and some can envisage a worldwide network of neutrino monitors contributing to anti-nuclear weapons proliferation efforts in the future[36].

7. Summary

The business of geoneutrino detection is already underway at existing large instruments and those being built. The first results are in hand, and they will continue to improve. The most desirable information about U and Th content of the mantle (and core) will not be obtained until a 10 kiloton scale deep ocean instrument is deployed. Hanohano is proposed for this task, but is at least several years from operations. Studies are underway for further improvements in detector sensitivity and directional capability.

Operation of the class of multi-kiloton neutrino detectors with MeV level sensitivities will not only open a new area in geology, but will make contributions to neutrino physics and astrophysics, and will pave the path towards the creation of networks of detectors for remote nuclear reactor monitoring. It would appear that there is a bright future in this emerging field.

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