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1. Goal

The aim of the programme Earth AntineutRino TomograpHy (EARTH) is to eventually make a 3D-map of the radiogenic heat sources of our planet. The 3D-tomography has to be achieved by direction-sensitive measurements of antineutrinos released in radiogenic processes such as natural decay and fission. Direction information is largely embedded in the neutron emitted as part of the antineutrino capture reaction on a proton.

Direction-sensitive antineutrino detection is also a very sought after tool for establishing fundamental properties of antineutrinos. Considerable progress has been made in neutrino physics in the past decade and one of the remaining questions (the value of the mixing angle θ_{13}) can be determined by direction-sensitive antineutrino detection (*P. Huber et al.,*2005*)*.

Antineutrinos are increasingly becoming a tool for monitoring nuclear power reactors. The work near the San Onofre Nuclear Generating System (SONGS) has demonstrated that antineutrinos can be measured in an underground geometry *(Bowden et al. 2007, and Bowden, 2008)* in the near vicinity of a nuclear power reactor (~25m from the core). Their intensity and spectral distribution are related to the power generated as well as the composition of the fuel. The International Atomic Energy Agency (IAEA) has stated that they like to have antineutrino detectors installed in and near, new and future types of nuclear power reactor *(IAEA, 2008)*. These detectors will be an integral part of the "safeguards by design". One of the first reactor types to be targeted is the Pebble Bed Modular Reactor (PBMR). The construction and operation of this reactor clearly indicates that direction-sensitive measurements, above ground are desirable.

2. Collaboration framework.

The idea for EARTH originated at the KVI, Groningen, but was moved to a Foundation (Stichting EARTH) founded by the University of Groningen, ASTRON and Stichting JADE, a private foundation. The Stichting EARTH has a Board as well as an Advisory Counciland is located in Peize, near Groningen.

Board Stichting EARTH:	**Advisory Council toEARTH:**
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The Stichting EARTH has established an official collaboration by means of a Memorandum of Understanding with the South African national laboratory iThemba LABS, the University of Stellenbosch (US), the University of Cape Town (UCT) and the University of the Western Cape (UWC), all four situated in the vicinity of Cape Town. In addition to this, there is collaboration with the Physics Department of the University of Jyväskylä, Finland, ASTRON and the Faculty of Earth and Life Sciences at the Vrije Universiteit, Amsterdam.

At the time of writing this report, a collaboration between Stichting EARTH and the recently established scientific and technical institute INCAS^3 in Assen, the Netherlands has started up and is in the process of drafting a Memorandum of Understanding between the two parties. In addition collaboration discussions have been started with the Kernfysisch Versneller Instituut, the University of Groningen (KVI). The development of direction-sensitive antineutrino detectors fits well within their present programme, but requires additional funding and personnel. The aim is to come to a collaboration between Stichting EARTH, the South African partners, INCAS^3 and KVI. The collaboration should preferably do their utmost to jointly search for a young scientist taking eventually a leading role in the programme, who is willing and able to apply for one of the grants of the Dutch Organisation for Scientific Research (NWO). In addition other sources of funding will be investigated.

In addition to a Board and an Advisory Council, the Stichting has established an Industrial Consortium of a number of companies in the (Northern) Netherlands. EARTH participates in Sensor Universe, a sensor development initiative by the three northern provinces in the Netherlands.

3. Developments and present status.

In order to ensure progress and reduce costs, a phased approach to the project was adopted from the outset, ramping up as each stage is successfully completed. The initial stage of the programme has focussed on two aspects: phase one, on detector development and testing as well as on the assessment of radiogenic sources based on the current scientific knowledge.

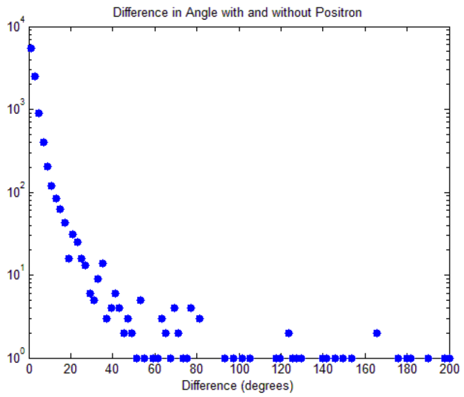

Figure 1. Frequency distribution for 10,000 events of the angle difference between positron-neutron line and antineutrino capture neutron line. (Jaco Blanckenberg)

3.a. Detector development.

The first phase of detector development was mainly carried out in South Africa by using the expertise, present at UCT (prof. Frank Brooks) and iThemba LABS (dr. F.D. Smit), on neutron detection. An existing small detector cell filled with scintillation liquid and loaded with 5% ^{10}B was used to mimic delayed coincidences and investigate the influence of pulse-shape properties. These tests were accompanied by Monte Carlo simulations of the neutron capture process both for captured antineutrinos from natural decay as well as fission. The simulations stress the need for the early capture of the neutron to preserve the direction information carried by the incoming antineutrino. The results have been published (de Meijer *et al*, 2006) and (Smit *et al,* 2006).

Subsequently, Monte Carlo simulations have been expanded to also include the positron properties. These simulations are presently being carried out at the Universities of Cape Town and Stellenbosch as part of MSc projects of Matthew Segal and Jaco Blanckenberg, respectively. The two students received a stipend from Foundation JADE. These simulations done by the two students indicate that the distance travelled by the positron is so small that the line between the neutron capture and the average positron position is a rather accurate approximation of the line between the location of antineutrino detection and neutron capture. Figure 1 shows a frequency distribution based on a simulation by Jaco Blanckenberg of 10,000 events.

Matthew Segal has been using the Monte Carlo N-Particle Transport Code MCNPX, to make simulations of the interactions of neutrons from an Am-Be source and natural and isotopically enriched B loaded scintillators. One of the parameters he has been calculating is the time from when a neutron first scatters sufficiently to make a signal generated by the recoil proton and when it is captured by ^{10}B. This double-pulse signal is similar to that needed to identify antineutrinos captured in the same scintillators. The results are presented in Figure 2 and will be tested for in the laboratory.

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In parallel to the detector tests at the Cape, EARTH purchased boron-doped plastic detectors and made them available to researchers at the University of Groningen and one of the industrial partners. They developed an algorithm that allows pulse-shape analysis of fast digitised pulses. Their work also demonstrated that under optimal conditions, a time difference of 10ps could be measured for pulse-generator pulses with a rise time of 4 ns. Time-difference measurements of this order of magnitude, in principle, open new avenues for direction-sensitive measurements of antineutrinos. Accurate time measurements of the positions of the positron and the neutron capture can provide a position difference vector that can be used as an estimate of the incoming antineutrino direction.

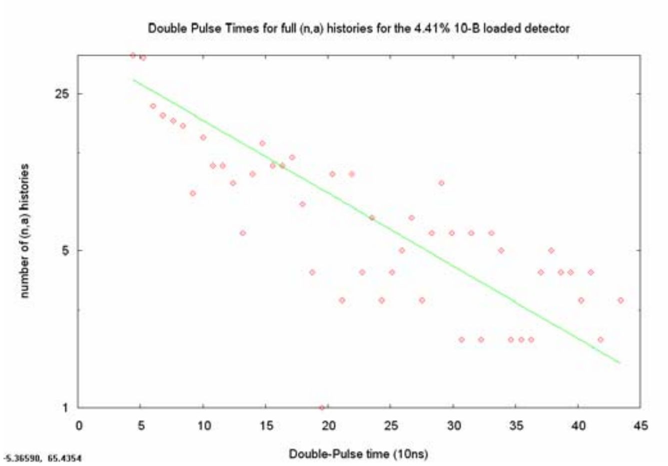

Figure 2. Simulated histogram of time between the first significant neutron scattering and neutron capture in a scintillation liquid exposed to neutrons from a Am-Be source. (Matthew Segal)

Based on this achievement, a design for GiZA (Geoneutrinos in ZA), a detector that could be used for the next phase, was decided on. The main function of this detector will be the precise characterisation of an antineutrino event by measuring pulse height properties of

Figure 3. A test cell filled with liquid scintillator equipped with two PMTs

both the positron and neutron-capture signals, as well as their timing properties. With this detector estimates of the background reduction achievable, will also be tested. To obtain sufficient counting statistics in a reasonable time frame, a ~40 litre, tetrahedron-shaped detector with a PMT at each corner has been proposed. The optical properties of this detector have been optimised done by ASTRON using ray-tracing simulations. This work, a contribution in kind by ASTRON to Stichting EARTH, has been completed and the mechanical construction is nearly finished. A more detailed discussion on GiZA is presented in section 4.a.

It is envisaged to optimize the scintillation liquid in a parallel development. For that purpose a number of small test cells have been designed and constructed by SCIONIX Holland B.V.. The design and the construction of the cells as well as their filling have been financed by Stichting Sensor Universe as part of a plausibility study. The cells, with a length of 10cm and a diameter of 5cm, have a photomultiplier tube mounted on both sides. These photomultiplier tubes were donated as a contribution in kind by PHOTONIS. A photograph of the set-up is shown in Figure 3. Two cells have been filled with scintillation liquids, differing in

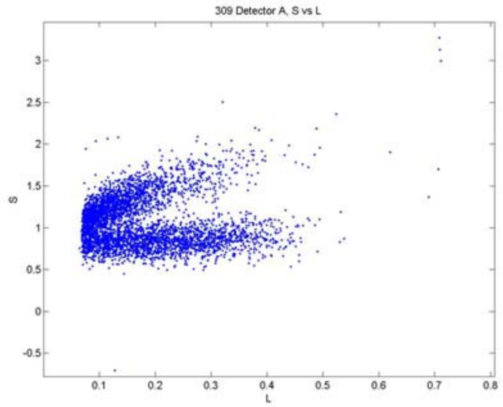

Figure 4 An example of the pulse-shape discrimination achieved with one of the EARTH scintillators filled with EJ309. In the figure pulse shape is on the y-axis and pulse height on the x-axis. The detected neutrons (top locus) and the gamma-rays (bottom locus) are clearly separated.

^{10}B content and chemical properties. They are presently being tested at iThemba LABS. Based on the results, a decision on the first liquid with which to fill the GiZA detector will be made. The two remaining cells will be reserved for testing some of the new scintillating materials to be developed. (see section 4.c).

The two filled test cells are presently being tested at iThemba LABS. The signals from the PMTs are fed into a digital scope (TEXTRONIX 3014) and stored on disc for off-line analysis. In these tests an Am-Be neutron-gamma source is used. One of the first tests was to investigate the pulse-shape discrimination potential of the two liquids. Figure 4 shows the preliminary results for a cell filled with EJ309. The figure shows the pulse shape as function of pulse height and shows to clear bands of data. The top band represents recoil protons from neutrons scattering off H, and the bottom band being events corresponding to gamma-rays. For antineutrinos the α-pulses due to the capture of neutrons by ^{10}B will be in the top band and the bottom band will contain the positron pulses. The figure shows that we may expect the neutron and positron events to clearly be separated.

3.b. Assessment of radiogenic heat sources in the Earth's interior.

Recent developments in geochemical models and increases in precision of isotopic dating techniques have led to new insights on the early history (< 100 Ma) of our planet and its moon. The present knowledge leads to a concentration of U, Th and Pu in the Core-Mantle Boundary (CMB) or D" region. About two years ago it was realised that under the prevailing temperatures and pressures in the CMB a mineral, calcium perovskite, is formed that absorbs U, Th and Pu several orders of magnitude more readily than the other dominant minerals in the CMB. If the CMB was homogeneous these actinides would be nicely dispersed over the CMB and therefore decay naturally (including spontaneous fission). Heterogeneities however, e.g. due to density effects, leading to pockets of material with an order of magnitude higher concentration of these actinides would create a situation in which a natural georeactor could ignite and stay operational, even possibly up to present.

In a paper (*de Meijer and van Westrenen*, 2008, see also *Ball*, 2008) the consequences of such a georeactor are sketched. In addition, the possible identification and location of such georeactors by antineutrino tomography could lead to accepting changes in the isotopic composition of a number of elements, most clearly in He and Xe, relative to their abundances in the Earth's atmosphere. The calculated isotopic ratios are consistent with the deviating isotopic compositions in gasses from deep wells.

Triggered by the work on geoneutrinos and georeactors, a popular scientific book was written in Dutch "Hoe werkt de Aarde?" ("How does the Earth work") (*de Meijer and van Westrenen*, 2009). The book was launched at a special symposium organized by Stichting Sensor Universe on 14 May 2009.

A further trigger lead to the question: what happens when a georeactor becomes supercritical? Working out an answer lead to an alternative hypothesis on the origin of the Moon. In this hypothesis the energy released by the supercritical georeactor heats up it surroundings to very high levels, vaporising all materials and creating a vapour bubble working its way to the surface and expelling the material from which the Moon is eventually formed. A paper on the hypothesis has been submitted to an international scientific journal and is still under review.

4. Plans for the near future.

4.a Detector development GiZA.

The experimental work with the small test cells together with computer simulations have lead to progress in understanding the possibilities for direction-sensitive antineutrino detection. We have reached the stage in which real antineutrino signals have to be detected. Their properties have to characterised and compared to other background signals produced when placing a detector near a strong antineutrino source: a nuclear power reactor.

Initially we developed our ideas along the line of a honeycomb detector consisting of a number of long detectors either tubular or with a square diameter along the lines as worked out in our papers (de Meijer *et al*, 2006) and (Smit *et al,* 2006). Using detectors with such shapes would result in the shape contributing to identifying the direction of the incoming antineutrinos. The results with the SONGS detector (e.g. N.S. Bowden, 2008) showed that with a 600 litre detector and an efficiency for counting antineutrino events of 10%, a count rate of about 600 events per day were measured, of which about 150 were due to unsuppressed background. Aiming for an efficiency of 30%, a detector system of 40 litres would lead to a net count-rate of 90 real antineutrino events per day at a distance of 25m from a 3 GW_{th} reactor. In a measuring period of a month, sufficient statistics can be collected to study the antineutrino energy spectrum. These numbers however represent net count rates leading to an additional question of whether the counts can be distinguished from background events.

To obtain a total of 40 litres with 1m long, 5 cm diameter tubular detectors would require about 20 detectors, each requiring two PMTs and associated electronics. This number may further increase if the lengths of the detectors have to be shortened because of light collection limitations. Even a 20 detector systems requires a high investment in PMTs and electronics and already makes the data collection and data analysis system quite complex. It was therefore decided to start with a more simple system, containing four PMTs and a single volume of about 40 litres. Choosing a tetrahedron shape is one of the most compact forms and, in principle, allows position determination by triangulation measurements of the arrival times and magnitude differences of the scintillation signals.

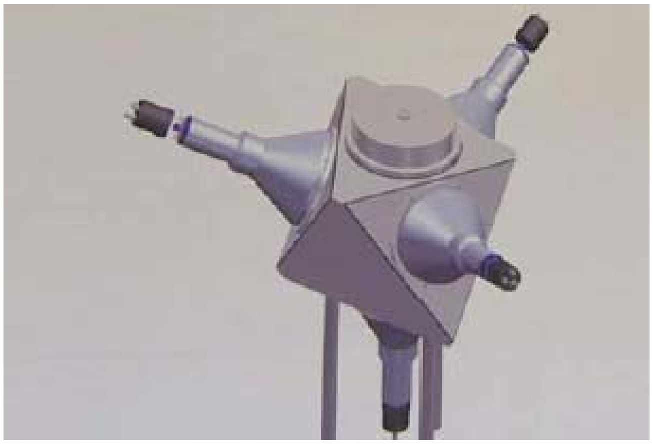

Figure 5. The GiZA detector according to one of the latest design studies.

Using ray-tracing software at ASTRON, the optical properties of the GiZA detector were optimised. One of the choices to be made was on the properties of the walls. Shiny, mirroring walls would enhance the photon detection efficiency, but as a consequence the timing information would be smeared out. For that reasons the inner walls of the detector will be made black, allowing only detection of direct photons. Signals from the capture neutrons by Boron are however small. For this reason alight-guide system is used to enhance the solid angle of the PMTs. Based on these light simulations by ASTRON, SCIONIX Holland B.V. has almost finished a mechanical design for GiZA. A drawing of one of the latest stages of the detector is shown in Figure 5.

A common characteristic of all antineutrino detector systems is a low true count rate compared to background count rate. It is estimated that a background count rate of 1 to 10 kHz can be expected in GiZA, corresponding to a total event rate of about 10^8 to 10^9 events per day. At a $3GW_{th}$ nuclear power reactor at a distance of 20 to 25 m we estimate, based on the experiences at the SONGS experiments (see above), a count rate of about 10^2 antineutrino events per day. Aiming at a background count rate of 10% of the total count rate requires a background reduction factor of 10^7 to 10^8. Assuming that the background is uncorrelated in time we expect that such a reduction factor will be achievable.

Table 1: Background reduction factors and their expected effect.

Delayed anti-coincidence	Active shielding	Pulse-shape discrimantion	Constant energy α-pulse	Position constraint	**Total**
10^6	10^2-10^3	10^1-10^2	10^1-10^2	10^1	**10^{11}-10^{14}**

Table 1 lists the various reduction steps and their effect. As seen from table 1 we expect a major reduction in the count rate by setting a time window of about 1 μs for delayed anti-coincidences between the positron and neutron-induced α-pulse. This is one of the great advantages of the boron doped scintillation liquids over the traditional capture by H or Gd. The next considerable reduction comes from anti-coincidences with active shielding against gamma-rays and cosmic radiation by surrounding the detector with plastic scintillator detectors. The energy of the α-particle produced in the capture by ^{10}B is almost independent on the energy of the antineutrino, due to a high Q-value for the capture reaction. This allows us to set an energy window in the pulse-height spectrum for the α-pulse. The positron and α-pulse is not only restricted in their time difference but also in the relative distance. Together with the pulse-shape discrimination, this constraint will help us to reduce the number of events induced by neutrons that have been able to pass the containment of the reactor. All factors considered we expect a background reduction factor that will be more than sufficient to suppress uncorrelated background.

We would like to point out that background due to gamma-rays from the building or due to cosmic radiation depends on the sizes of a detector. In our system of a modular set-up with a relatively small volume, the chances of being able to use such detectors above ground has also increased. The main reason is if the detector becomes too large the background count rate becomes so large that the system gets overloaded with background events and various types of passive shielding will be required. The tests with GiZA, anticipated at the Koeberg Nuclear Power Stations near Cape Town, will determine to what extent our reasoning is correct.

Of course, to a large extent the system can already be tested in the laboratory using neutron sources. We prefer to make use of digital electronics, so that all corrections can be optimised in offline analysis. Therefore extensive laboratory tests will be carried out prior to deployment at Koeberg Nuclear Power Stations.

Smaller test cells, filled with a scintillation material from which a choice will be made for filling the GiZA detector, have become available for testing in the laboratory. **We would like to again stress that for this stage of the tests, using GiZA, direction sensitivity is not the main issue. The tests concentrate on antineutrino identification, testing position determination by means of triangulation as well as background reduction.** Knowledge gained from these tests will be incorporated into a proto-type detector design. With **this** proto-type direction sensitivity will be tested, and if successful, this detector will be the step towards a detector system for monitoring and safeguarding nuclear power plants.

4.b. Reactor Monitoring.

In the discussions at the Focused Workshop on Antineutrino Detection for Safeguards Applications held at the IAEA Headquarters, Vienna, from 28-30 October 2008, we proposed a two parallel line approach. One was to "copy" a SONGS like detector while the other was the further detector development following on from GiZA. The first line is taken because it represents a proven technology on which we can work and improve using experiences and insights obtained in the development of the GiZA detector. This approach was agreed upon in Vienna and the LLNL-group offered to collaborate with us. On 10 December 2008 this approach was welcomed by the Bestuurlijk Platform (Governing Board) of Sensor Universe. They supported the approach and will try to match funding obtained from other sources.

The South African partners have indicated that they would like to continue to concentrate on the GiZA development and would like to see another institution take over the constructing of a SONGS-like detector.

4.c. New scintillation materials.

The technology of scintillation liquids for neutron detection dates from the middle of the last century and there has been very little development since then. It is therefore quite reasonable to expect that there have been material developments which could assist us in removing some of the disadvantages of the traditional liquid scintillation materials. These disadvantages include a low-flash point, toxicity, and the most important to our work, a strong quenching of the neutron-induced α-particle signal. This signal reduction brings the α-pulse height from about 2.5 MeV to a 60-100 keV signal in the energy spectrum. As a consequence it is much harder to distinguish the signal in the more intensive continuum part of the spectrum.

To search for solutions, the University of Groningen spin-off company Polyvation B.V., in collaboration with Stichting EARTH, has made a feasibility study on developing new scintillation materials in a project sponsored by Stichting Sensor Universe. They conclude that they have identified a number of potential alternatives for the scintillation material as well as compounds of materials with suitable properties. They propose a continuation in collaboration with a number of companies, to do further work on some of these alternatives and test them in the spare test cells, described in section 3.a.

4.c. Assessment of radiogenic heat sources in the Earth's interior.

The work on the radiogenic heat sources will continue. For georeactors in the CMB, a model is being developed linking a supercritical georeactor to the formation of the Moon. Work has started on assessing the role that georeactors may have played also in other planets of our solar system. For Earth the role centres on the issues of mantle plumes, large scale mineralisations (e.g. of gold and platinum in Africa) and abiotic natural gas in the deeper parts of the Earth (eg. possibly the recent gas fields off the Brazilian coast)

4.d. Financing.

As in the past, we concentrate on Public-Private Partnerships for financing the development of our programme. With clear applications in sight, we have received encouraging support for the near future financing of our plans.

With pleasure and gratitude we acknowledge a gift to the Stichting by a company in Groningen, NL.

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