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Preface

On 11 March 2011, Fukushima Daiichi nuclear disaster
(福島第一原子力発電所事故) , **focused worldwide attention on potential impact and implications of radiation damage from nuclear energy plants like never before. Popular information and communication networks enabled nuclear experts to compete with political radical non-experts on equal footing. Not knowing what happened exactly during the earthquake and to what extend it effected the plant and the environment led to wild speculations.**

The public massively engulfed in hypothetical doomsday scenarios. Uncertainty which seemed to grow by the day became the big feeder of widespread fear. Even today, more than a year later, many question marks remain unanswered.

EARTH, a research project, initially preoccupied with geo-nuclear issues, had long realized its potential as an anti-neutrino monitoring device for nuclear energy plants. Therefore, accentuated and accelerated by the Fukushima Daiichi incident, the EARTH-team focused its research and development towards building a real time measuring device for nuclear plant monitoring.

The testing of prototypes in laboratory settings has made considerable progress in a relatively brief period, resulting in our Compact Antineutrino Monitors REACTOR-CAM that could become available to the nuclear energy markets within a few years.

It may appear to some, that EARTH's significant break through research diverted the team away from its initial geo-nuclear objectives. But recent revolutionary manuscript about the origin of the Moon, proof differently.

Proudly, the EARTH team presents this progress report, which is merely a prelude to a total change in nuclear energy safety regulation monitoring. With great confidence we look forward to the future, which, by all means, is promising a much safer world for nuclear energy than ever before.

Amsterdam, 30 August 2012
Jacob Gelt Dekker
Chairman Board Stichting Earth AntineutRino TomograpHy

1. Introduction.

This report presents the progress of the EARTH programme since the last report, published in December 2010. An earlier report, EARTH PRP-007, published in July 2009 gave a comprehensive overview of the project and the reader is referred to EARTH PRP-007 for further details and background information.

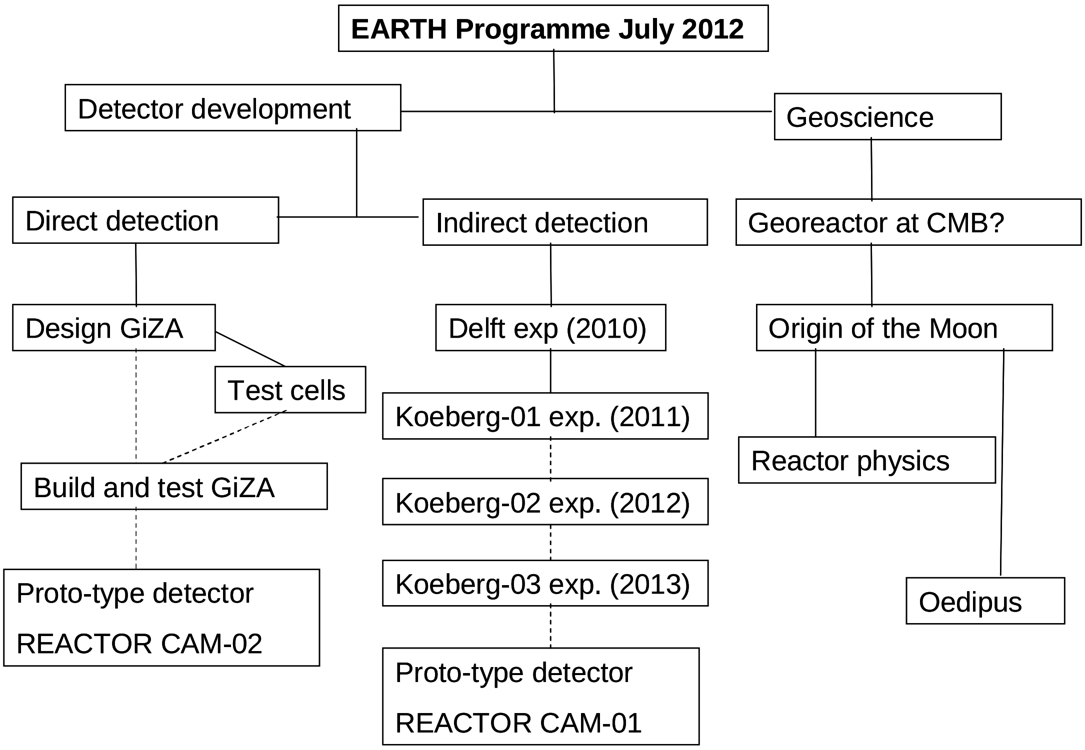

Figure 1. Schematic overview of various activities within the EARTH programme as at July 2012. The solid connecting lines indicate past and ongoing activities while the dashed lines are projections into the future.

The present and planned activities within the EARTH programme have schematically been presented in Fig. 1. The solid lines indicate the parts of the programme, being either completed or in progress. The programme has two main activities: Antineutrino detector development and Geoscience aspects that could result from the eventual data collection of antineutrinos emitted by various radiogenic processes in Earth. The present update will be structured according to this scheme.

2. Detector development.

2.1 Direct detection of antineutrinos

Here the term "direct detection" refers to the commonly used reaction in which an antineutrino is captured by a proton and the reaction products, a positron and a neutron, are detected. Commonly the positron and neutron are detected by gamma-rays emitted subsequent to annihilation and capture, respectively. This method however, has no direction sensitivity as the long range of the gamma radiation hampers the efficiency of compact detectors. In our approach the slowdown signal of the positron and the capture of the neutron by ^{10}B are anticipated to produce the signals. After neutron capture, ^{11}B decays by alpha particles to ^{7}Li. This implies that our detector material produces signals that allow differentiation between the various particles.

During the present reporting period the work started during the MSc work of Jacco Blanckenberg, has been continued. With financial support of the South African National Research Foundation, electronics could be purchased and built up in a special neutron detection set-up at iThemba LABS (iTL). This part was carried out under the supervision of Prof. A. Buffler (UCT). The set-up contains special modules that allows pulse-shape differentiation (PSD) to be carried out. Our measurements focussed on the cell filled the liquid scintillator material EJ 309, loaded with 5% natural Boron. The great practical advantage of this liquid is its relatively high flame point (+144˚C) and the fact that EJ309 is not on the list of dangerous goods.

Two geometries are in principle considered in the EARTH programme: a tetrahedron shaped detector, GiZA, and a multi-tubular detector system. To prepare for a test detector with sufficient count rate at a measurement near a nuclear power reactor, two small cells were purchased to explore the possibilities and limitations for antineutrino detection. In Figure 2 a cell sandwiched between two Photonis photomultipliers (PMTs) can be seen.


Figure 2. A 15cm long, 7.5 cm diameter test cell, sandwiched between two PMTs.

In February 2011, one of the first achievements obtained with these cells was that we could conclude that a new scintillation material had two major advantages: a much higher flame point and better quenching properties. The first property removed the scintillation material from the lists of dangerous goods, the second one allowed us a better signal for pulse-shape discrimination (PSD). An example of the PSD is presented in Figure 3. Clockwise from the top one notices loci corresponding to α-particles, fast neutrons and γ-rays.

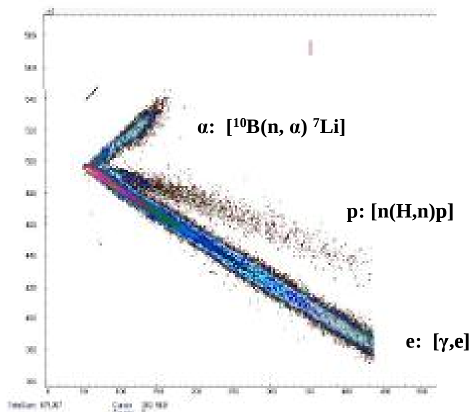

Figure 3. PSD with the EJ309 scintillation liquid. For the interpretation of the loci see text.

The results in Figure 3 indicate a very good differentiation between the signals produced by α-particles, fast neutrons and electrons during a background measurement in one of the vaults at iTL. At the time of the measurement the cyclotron was off. Initially we attributed the signals to α-particles produced by capture of slow neutrons by ^{10}B, protons produced as recoils of fast neutrons and electrons from γ-radiation all originating of the interaction of cosmic rays with the materials surrounding the detector. Moreover we noticed that the count rate in the locus of the α-particles, was not constant and showed sharp peaks. An example of such a background spectrum with count rate peaks is shown in figure 4. In addition to the peaks one notices that the initial continuum count rate is a factor of 2 higher than after the peak around t=25h.

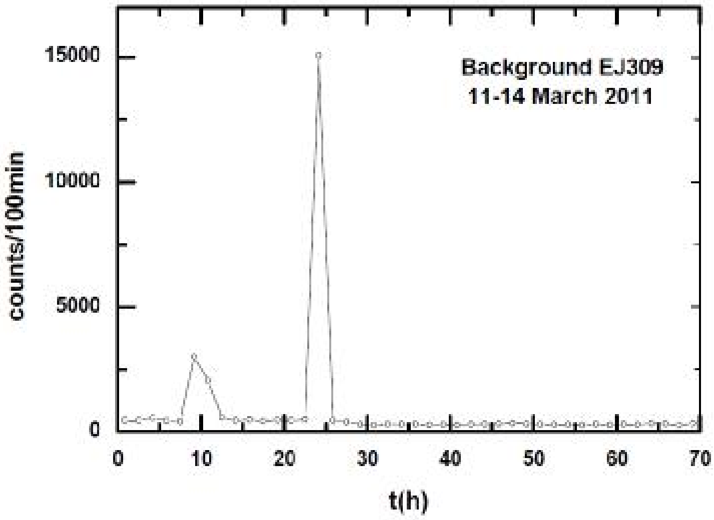

Figure 4. Count rate during a background measurement on 11-14 March 2011. The solid line connects the data

At present we still have no explanation for these peaks, but e.g. we noticed that during such a high count rate period, the count rate dropped when the set-up was rolled out of the concrete vault. In view of the start of experiments at Koeberg (see section 2.3.1), the work was temporarily halted but is intended to continue soon. The work thus far has been carried out in the framework of the PhD thesis of a University of Stellenbosch student, Milton van Rooy. The continuation may likely be the topic for another PhD student.

2.3 Indirect detection of antineutrinos.

2.3.1 Koeberg-01 measurements

In our previous progress report we summarised the work carried out at the 2 MW research reactor at Delft University of Technology, the Netherlands. This work has been published in the meantime. (*de Meijer, Blaauw and Smit, 2011)*. The conclusion of that work was that the cross section for antineutrinos affecting the nuclear β^+-decay was two orders of magnitude smaller than the effect hypothesised to explain the oscillations in the decay curve of ^{32}Si as being due to variations in the solar neutrino flux resulting from annual variations in the Sun-Earth distance. (see e.g. *Jenkins et al., 2009)*. This new upper limit, however, was still large enough for a possible effect to be observed at a distance of about 30m from a $1GW_e$ nuclear power plant.

Access was permitted to place a scintillation counter, a β^+-source, electronics and a laptop computer in one of the nearby passages outside of the containment wall of Unit#2 of the Koeberg Nuclear Power Station, situated at about 30km north of Cape

Town. The power plant houses two 0.9 GW_e units. Measurements started while Unit#1 was on full power, whereas Unit#2 was down for refuelling and maintenance. The distance to the cores of the reactors was 66 and 23m, respectively. Both prior to and after this measurements with and without source were made at iTL. At Koeberg and iTL data were collected at 10 minute intervals and stored into the memory of the laptop. Roughly at weekly intervals the data collected at Koeberg was sent to iTL. The measurements at Koeberg started with a background measurement (BG) followed by a measurement with a source. The measurements were followed by BG and source measurement at iTL. The entire measurement series started in April 2011 and lasted until the end of August 2011. This period spanned the time when Unit#2 went back to full power.

Most likely due to the high air temperature (> 30 °C), troubles developedover time with the (brand new) main amplifier, which eventually had to be replaced. Unfortunately this occurred at the time that Unit#2 was starting up.

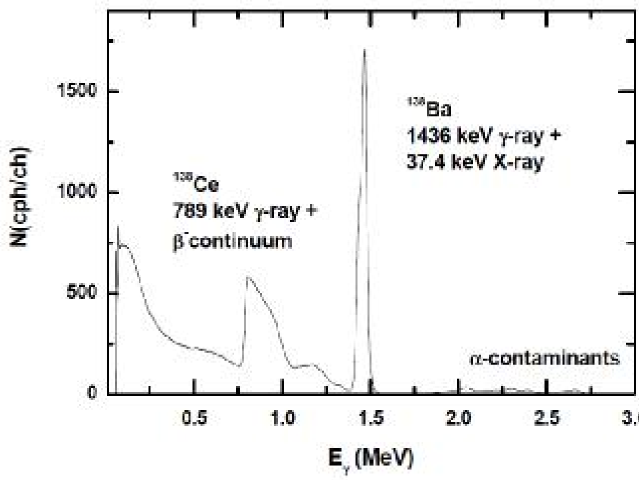

Figure 5. Background spectrum of the $LaBr_3$ detector used in our measurements

The scintillator detector was a 3”*3” $LaBr_3$ detector which we gratefully got on loan from the European Space Agency, Noordwijk, the Netherlands through the Delft University of Technology. $LaBr_3$ has an energy resolution superior to the more commonly used NaI and in addition is intrinsically active due to the naturally radioactive ^{138}La. This radionuclide has decay properties which are very useful for this study. A BG spectrum is shown in Figure 5. In the spectrum one recognises the broad bump at about 0.8 MeV caused by the β^- decay of ^{138}La to ^{138}Ce and a broadened peak near 1.5 MeV originating form the electron capture by ^{138}La leading to an excited state in ^{138}Ba, partly in coincidence summing with a 37.4 keV X-ray. At higher energies one notices structures caused by quenching of α-particle energies. These particles are emitted by ^{232}Th contamination of the detector material.

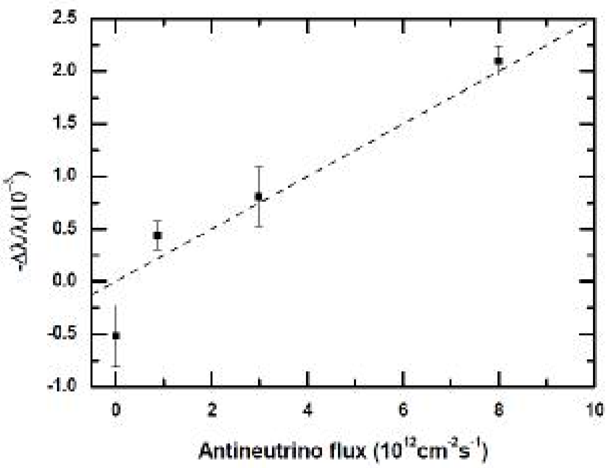

Figure 6. The change in decay constant as function of the estimated antineutrino flux.

In total the measurements at iTL and Koeberg lasted about

3000 hours. Spectra were gain matched, corrected for dead time and combined to one hour spectra. From the analysis of the BG-spectra it was deduced that there was a change in the count rate of the two structures of the ^{138}La decay between Reactor-ON and Reactor-OFF conditions of about (6±3)*10^{-4} at a change of antineutrino flux of about 8*10^{12} $cm^{-2}s^{-1}$. The ratio of the two structures remains within the statistical uncertainties unchanged. This flux is estimated assuming that only ^{235}U contributes to the power production, and the above distances to the core of the two units. This change corresponds to a cross section of (1.6±0.8)*10^{-35} cm^{-2}. The uncertainty only reflects statistical uncertainties and not possible systematic effects as e.g. due to change in amplifier. On the other hand, since the Reactor-ON and –OFF conditions also correspond to a change in amplifier, the systematic uncertainty is limited to about (6±3)*10^{-4}.

With the source placed close to the detector, a change in half-life of the source as function of the antineutrino flux was seen as shown in Figure 6. The results indicate a change of decay constant increasing linearly with the estimated antineutrino flux. The dashed line in Figure 6 represents the function.

$\frac{\Delta l}{l} = -2.5*10^{-16}*f(\overline{n_e})$, if the antineutrino flux $f(\overline{n_e})$ is expressed in $cm^{-2}s^{-1}$. This result was completely unexpected. It is unfortunate that we had to exchange the amplifier at the most crucial moment, although the observed effect is an order of magnitude larger than the possible systematic effect mentioned above. Another reason to doubt the validity of this result is the cross section of a few barn for this interaction of antineutrinos with our source nuclei. This cross section is 24 orders of magnitude larger than model calculations indicate and hence we seriously consider the above effect to be due to a flaw in the measurements or their interpretation. We therefore have undertaken a second series of measurements to confirm or deny the above results.

2.3.1 Koeberg-02 measurements

A second series of measurements was started in February 2012 and lasted until July 2012. This time the set-up at Koeberg was placed right under the core of Reactor Unit#1 at a distance of about 17m from its centre. The core and the set-up are separated from each other by some 6m of concrete. To reduce other systematic uncertainties as much as possible, we used a 3”*4” NaI detector. Based on the experience of the previous measurement series, the data were collected for 20 minute intervals. Moreover a HPGe detector was installed and run for some initial period of time, mainly to rule out neutron activation contributions to the γ-spectra efficient.

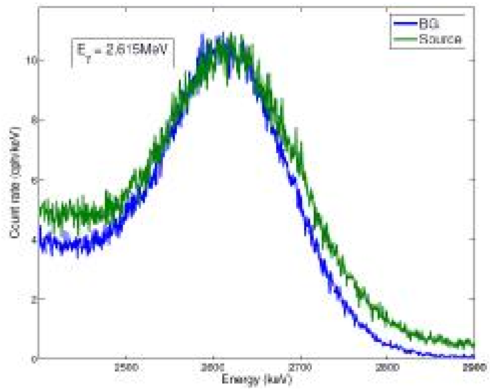

Figure 7. Shape of the 2.615 MeV background γ-ray in the presence and absence of our source.

At the start of these measurements at Koeberg, both units were at full power. After some time Unit#1 was shut down for refuelling and maintenance and returned to full power in May 2012. Measurements continued to the middle of July after which the detector was returned to iTL.

Shortly after the start of measurements with a source placed in front of the detector it became clear that we were encountering experimental problems. Contrary to the background measurements where the peak positions hardly changed with time, the measurements with the source showed a continuous drift of the peaks. More seriously is the shift in peak shape as e.g. demonstrated in Figure 7 for the 2.615 MeV belonging to the decay series of ^{232}Th present in the concrete surrounding the set-up. The figure shows a clear broadening of the peak. Moreover this broadening is dependent on the count rate and changes during the measurement. This prohibits accurate background subtraction. With the precision required in our analysis, the peak area determination is influenced by the change of the shape of the background spectrum. We are still in the process of trying other avenues of extracting reliable data, but seriously anticipate a third series of measurements after the problem has been identified and can be properly remedied.

Since the effect is only present with the source on we suspect an effect due to the source. Thus far we suspect bremstrahlung, as a result of the slow down of the β^+ particles, to be the cause of the trouble. Once the detector has been returned to iTL we will investigate the problem further.

This detector development is also part of the PhD work of Mr. Milton van Rooy. Dr. P.Papka, the university supervisor of Mr van Rooy was involved throughout the measurement at Koeberg. This work was made possible thanks to the help of dr. P. Dorenbos and dr. F.G.A. Quarati who made the $LaBr_3$ available for this experiment, as well as dr. S. Steyn and his collaborators at the Koeberg Nuclear Power Station for providing us with access to the facility. We would especially like to thank Ms. E. Welman and Mr. R. Steyn for their help in downloading and transmitting data from the set-up to us.

3. Neutrino Geoscience.

3.1. Introduction.

The long-term goal of the Stichting EARTH is to work towards obtaining a 3D-image of the distribution of radiogenic heat sources of Earth by means of antineutrino tomography. Although in the short term the present detector development focuses on reactor monitoring, the long-term goal remains unchanged. On the basis of the rapidly growing geoscience literature on these topics and in the absence of any data, we are exploring the nature of the radiogenic heat sources being either natural radioactive decay, or possibly a natural georeactor. In both cases antineutrinos will be emitted, but a distinction between the two types can be made from the energy information. As indicated in earlier work *(de Meijer and van Westrenen, 2008*) our present knowledge of geoscience can? not rule out georeactors in the CMB.

Presently the commonly accepted hypothesis on the formation of the Moon is that a relatively gentle collision between Earth and a Mars-sized celestial object lead to its formation. The present-day angular momentum of the Earth-Moon system, the small metallic core of the Moon compared to the large metallic core of Earth, and the relative masses of the Earth and Moon are all consistent with this hypothesis. However, according to numerical calculations of this ‘giant impact’ hypothesis, as a result of this collision the Moon should mostly (approximately 80%) be composed of the material from the impactor. In recent years the evidence deduced from elemental and isotopic analysis of lunar surface rocks increasingly stresses the similarities between the Moon and the mantle of the Earth. The composition information of the Moon therefore strongly suggests that the Moon originates from the Earth, in disagreement with the giant impact hypothesis.

One of the earliest hypotheses of the origin of the Moon is by George Darwin who suggested that the Moon was pulled out of a rapidly rotating Earth by the Sun. Both the initial hypothesis and subsequent modifications by Ringwood and Wise were rejected because in the absence of additional energy sources this scenario lacks the energy and momentum to end up with the present-day angular momentum and energy of the Earth-Moon system. Our contributions make the point that, since the missing energy should be supplied in a relatively short time, the only process that could supply this energy is a nuclear “explosion”.

3.2 Development

In the past year and a half we have made contact with dr V. F. Anisichkin of the Lavrentyev Institute of Hydrodynamics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia. In a joint paper, submitted to Chemical Geology, we re-examine the dynamics of the Earth-Moon system and the energetics of initial Earth-Moon separation. In contrast to previous ‘fission’ models, our conservative assumption is that the angular momentum of the proto-Earth before Moon formation is close to that of the present-day Earth-Moon system. This is in full agreement with assumptions made in recent three-dimensional hydrodynamic simulations of a giant impact origin for the Moon (Canup, 2008). We estimate the amount of energy required to separate the Moon from the

Earth in this case and propose nuclear fission as the only known natural process that could supply the missing energy in such a very short time.

We then show that it is feasible to form the Moon through the ejection of terrestrial silicate material due to a shock wave propagating through the Earth resulting from a nuclear explosion at Earth's core-mantle boundary (CMB), causing. Hydrodynamic modelling of this scenario (Anisichkin at al., 1999; Voronin, 2007, 2011) shows that a shock wave created by a rapidly expanding plasma resulting from such an explosion cracks and expels the overlying mantle and crust material. This can result in the formation of a Moon-sized silicate body in Earth orbit. The energy required for this to occur, although dependent on a wide range of poorly constrained variables, is well within the range of what can be produced by a nuclear explosion. Our hypothesis straightforwardly explains the chemical similarities between the Earth and the Moon, and connects the Moon formation with processes that took place following the Earth's early internal differentiation. Unlike previous 'fission' models (Ringwood, 1960; Wise, 1963, 1969) it does not rely on assuming an initial angular momentum of the Earth-Moon system that is much higher than presently observed.

U, Th and Pu concentrations in the CMB are insufficient to reach criticality. Additional concentrations can be achieved by a combination of two processes: growth of the relative concentration of the fissile materials by a transient pressure wave, induced by an impact at the Earth's surface (Anisichkin, 1997; Voronin and Anisichkin, 2001), and/or the development of compositional heterogeneities (de Meijer and Van Westrenen, 2008).

As shown by Voronin (2011) for fissile material at the CMB, an impact of a 100km-diameter asteroid can create a transient pressure increase of several TPa at the CMB, sufficient to concentrate fissile material from a subcritical to a supercritical reactor condition leading to an excursion. Regarding the development of compositional heterogeneities, it should be noted that even today small-scale heterogeneities exist in the core-mantle boundary region (e.g., van der Hilst et al., 2007): volumes exhibiting both higher-than-average and lower-than-average seismic wave propagation speeds, with diameters as small as 30 km, are now resolvable. Some studies suggest that the bottom of the mantle is partially molten today, forming a so-called 'basal magma ocean' (e.g. Williams and Garnero, 1996; Labrosse et al., 2007; Lee et al., 2010).

Although the precise nature and composition of these heterogeneities remains unresolved, this suggests that factors for significant local concentrations, in addition to the general CMB and CaPv enrichments described above, are entirely plausible even today.

The dynamics of the CMB 4.5 Ga ago are poorly explored. The higher rotation rate of the Earth at that time, and higher interior temperatures, are likely to have facilitated local concentrations of density heterogeneities to levels that exceed those currently observed, due to centrifugal forces and buoyancy effects associated with local heating.

A combination of impact-induced densification and compositional heterogeneity make a concentration factor of fifteen to twenty compared to the fully homogeneous scenario not unreasonable (de Meijer and van Westrenen, 2008).

Reactor physics calculations on the excursion of a georeactor indicate that the nuclear energy is released in a few milliseconds, creating a plasma with temperatures of the order of 10^{10} K and resulting in a shock wave. Anisichkin et al. (1999) and Voronin (2011) simulated the effects of their propagation through the silicate Earth. In these simulations energy and angular momentum are conserved. Figure 8 shows the time evolution of one of their hydrodynamic simulations. In this particular case, supercriticality of a CMB reactor is achieved by an impact of a 100km-diameter asteroid (body **1** in Figure 8) hitting, with a velocity of 30 km s^{-1}, a rapidly rotating differentiated Earth (with an equatorial radius of 7000 km) at the (Figure 8a).

In Figure 8c (~40 minutes after impact) the plasma and shock wave are shown to fragment the Earth's mantle and crust, with jets of plasma escaping to space. Approximately 1 hour after impact, fragments of crust and mantle are ejected into orbit (Figures 8d,-e,-f). In this particular simulation, the Moon (fragment **8** in Figures 8c,-d) is still part of the remaining Earth at this stage. The Earth returns to a more spherical shape with the Moon attached by a thin 'neck' (Figure 8g), which detaches from the Earth approximately 3 hours after the impact-triggered excursion (Figure 8h). Other fragments return to Earth or are lost to space depending on their energy and angular momentum. The final Earth:Moon mass ratio in this particular simulation agrees with observation, and the Moon is essentially fully comprised of terrestrial silicate material.

The Anisichkin (1999) and Voronin (2007, 2011) models provide a proof-of-concept of the Moon formation scenario we propose. The required fission energy depends on the assumptions made in the simulation. For example, the required energy increases with decreasing rotation speed of the Earth, decreasing equatorial radius, and increasing mass of the proto-Earth. Clearly, at this stage, only a limited number of hydrodynamic simulations of this scenario have been conducted, and large parts of parameter space remains to be explored. For example, a recent study by Ćuk and Stewart (2012) suggests that the Earth-Moon system may lose a significant portion of its angular momentum shortly after its formation due to resonances between the Moon, the Earth's core, and the Sun. If this is correct, the angular momentum constraint

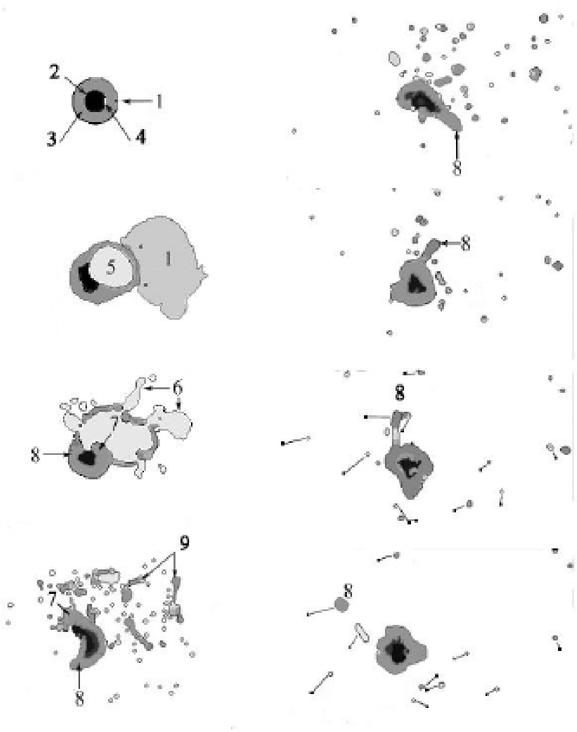

Figure 8a-8h(top-right to left-bottom). Snapshots of hydrodynamic simulations of Moon formation (Voronin 2011). **1** – asteroid and its products; **2** – Earth's core; **3**&**7** – mantle; **4** – location of nuclear explosion; **5, 6** – explosion products / plasma; **8** - separating Moon-like fragment on lunar formation models is too conservative and may be relaxed.

The end member models we have discussed above provide estimates for the range of fission energy required to form the Moon. Hydrodynamic models leading to the formation of the Moon as shown in Figure 5, starting with a 7000 km radius Earth and a fast 3 h rotation period, require a minimum fission energy of $0.6*10^{29}$ J (Voronin, 2007, 2011). In our discussion of the Earth-Moon dynamics, we assumed an initial ~6000 km radius for the Earth with a conservative rotation period of 5.8 h and derived a required fission energy of $2.5*10^{30}$ J. The next question to be addressed is whether the U-Th inventory of the CMB is sufficient to provide between $0.6*10^{29}$ J and $2.5*10^{30}$ J of fission energy.

Presented in Table 1 are the total amounts of ^{232}Th, ^{235}U and ^{238}U in the combined Earth Crust, Mantle and CMB according to a commonly used Bulk Silicate Earth (BSE) compositional model (McDonough, 2003) for both the present and 4.5 Ga ago. From Table 1 one may calculate that fission of 1 kg of a natural mixture at t = -4.5 Ga of ^{232}Th, ^{235}U and ^{238}U yielded $8.21*10^{13}$ J. Consequently, it requires fissioning of $7.3\text{-}320*10^{14}$ kg of the natural (U+Th) mixture to separate the Moon from the Earth at t = -4.5 Ga for the two models discussed in this report. The concentration of (U+Th) necessary for a georeactor to become critical is estimated to be of the order of 150 ppm (U+Th) (de Meijer and van Westrenen, 2008). Hence the corresponding mass of CMB material involved is of the order of $4.9\text{-}210*10^{18}$ kg. At a silicate rock density at CMB conditions close to $5.5*10^{3}$ kg m^{-3}, as derived from seismic observations (e.g. Dziewonski and Anderson, 1981), this mass corresponds to a sphere with a radius of approximately 60-210 km. Of course the shape of the reactor would not necessarily be spherical, but this first approximation calculation demonstrates that such a volume is fully compatible with our present understanding of the likely dimensions of a 'hidden reservoir' near the CMB.

Table 1. Masses and isotopic abundances of Th and U isotopes in the Bulk Silicate Earth (BSE) (McDonough, 2003)

	^{232}Th	^{235}U	^{238}U	Total mass
$t_{1/2}$ (Ga)	14.05	0.70	4.47	
m (10^{17} kg) (t = 0)	3.15	$5.87*10^{-3}$	0.80	3.95
Isotopic abundance (t = 0)	100%	0.73%	99.27%	
m (10^{17} kg).(t = -4.5 Ga)	3.94	0.52	1.62	6.06
Isotopic abundance (t = -4.5 Ga)	100%	24.3%	75.7%	

The maximum required mass of $320*10^{14}$ kg of the natural (U+Th) mixture corresponds to 5% of the fissionable (U+Th) in the BSE at t = -4.5 Ga. If approximately half of the BSE (U+Th) budget was concentrated in the CMB, as proposed by Tolstikhin and Hofmann (2005) and Tolstikhin et al. (2006), this corresponds to a maximum of ~ 25% of the CMB (U+Th) content. The minimum required values are ~60 times smaller than these maximum values. This range of percentages does not seem unrealistic.

In conclusion we state that all Moon formation models have to be consistent with lunar chemistry. Current versions of the giant impact model are not. Alternative models in which the Moon is formed from terrestrial material, deserve more detailed study. Here such an alternative model is provided. We show that a nuclear explosion in the CMB can provide the missing energy source required for the Darwin-Ringwood-Wise fission model for Moon formation. Our hypothesis not only provides a straightforward explanation for the striking similarity in elemental and isotopic composition of the Earth's mantle and lunar rocks, but is also consistent with the sequence of differentiation events which took place during our planet's earliest history. Future Moon missions returning with lunar samples taken at greater depths could provide supportive evidence for the validity of our hypothesis. The ^{3}He content and xenon isotopic ratios in particular, would be a crucial test of this hypothesis.

4. References.

Anisichkin, V.F., 1999. On explosions of planets. Proc. Int. Conf. V. Zababakhin Sci. Talks, 62-66.

Anisichkin, V.F., 1997. Do planets burst? Comb. Expl. Shock Waves 33, 117-120.

Canup, R.M., 2008. Lunar forming collisions with pre-impact rotation. Icarus 196, 518-538.

Ćuk, M. Stewart, S. T., 2012. Resonances and the angular momentum of the Earth-Moon system. Early Solar System Impact Bombardment II, 4006.

Dziewonski, A.M., Anderson, D.L., 1981. Preliminary Reference Earth Model (PREM). Phys. Earth Planet. Int. 25, 297-335.

van der Hilst, R.D., de Hoop, M.V., Wang, P., Shim, S.-H., Ma, P., Tenorio, L., 2007. Seismostratigraphy and thermal structure of Earth's core-mantle boundary region. Science 315, 1813-1817.

Jenkins, J.H., et al., 2009. Evidence for Correlations Between Nuclear Decay Rates and Earth-Sun Distance, Astroparticle Physics 32, 42-46.

Labrosse, S., Hernlund, J.W., Coltice, N., 2007. A crystallizing dense magma ocean at the base of the Earth's mantle. Nature 450, 866-869.

Lee, C.-T., Luffi, P., Hoink, T., Li, J., Dasgupta, R., Hernlund, J., 2010. Upside-down differentiation and generation of a 'primordial' lower mantle. Nature 463, 930–933.

McDonough, W.F., 2003, Treatise of Geochemistry, volume 2, chapter 18 (Elsevier)

de Meijer, R.J. and van Westrenen, W., 2008. The feasibility and implications of nuclear georeactors in Earth's core-mantle boundary region, South African Journal of Science, **104**, 111-118.

de Meijer, R.J., Blaauw, M, and Smit, F.D., 2011. No evidence for antineutrinos significantly influencing exponential β^+ decay, Applied Radiation and Isotopes, **69,** 320-326. doi:10.1016/j.apradiso.2010.08.002..

Ringwood, A.E., 1960. Some aspects of the thermal evolution of the Earth. Geochim. Cosmochim. Acta 20, 241-249.

Tolstikhin, I., Hofmann, A.W., 2005. Early crust on top of the Earth's core. Phys. Earth Planet. Int. 148, 109-130.

Tolstikhin, I., Kramers, J.D., Hofmann, A.W., 2006. A chemical Earth model with whole mantle convection: The importance of a core-mantle boundary layer (D") and its early formation. Chem. Geol. 226, 79-99.

Voronin, D.V., 2007. Generation of the Moon and some other celestial bodies due to explosion in planet interiors. Int. J. Geol. 1, 16-21.

Voronin, D.V., 2011. Computer modeling of planet partial fragmentation. WSEAS Trans. Fluid Mech. 1, 32-50.

Voronin D.V., Anisichkin, V.F., 2001. Simulation of the behaviour of mixtures of heavy particles behind a shock-wave front. Comb. Expl. Shock Waves 37, 470-474.

Williams, Q., and Garnero, E. J., 1996. Seismic evidence for partial melt at the base of the Earth's mantle. Science 273, 1528–1530.

Wise, D.U., 1963. An origin of the Moon by Fission during Formation of the Earth's Core. J. Geophys. Res. 68, 1547-1554.

Wise, D.U., 1969. Origin of the Moon from the Earth: some new mechanisms and comparisons. J. Geophys. Res. 74, 6034-6045.