POTASSIUM GEONEUTRINOS AND THEIR DETECTION

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ABSTRACT

The largely unexplored deep interior of the Earth results in a lack of knowledge of the Earth's composition and the processes taking place at different depths which leads to large uncertainties in Earth's energy production. The decay of the unstable isotopes of uranium (U), thorium (Th) and potassium (K) within the Earth produces a significant amount of heat that contributes to the overall Earth's energy output (Anderson 1989; Araki et al. 2005; Fields et al. 2004; Fiorentini et al. 2005; 2007). The radiogenic heating helps power plate tectonics, hot spot volcanism, mantle convection, and possibly the geo-dynamo. The composition of the crust is generally well characterized but good understanding of the concentration and distribution of U/Th/K in the mantle and the core is still needed to understand the terrestrial heat flow, the present composition, and the origins of the Earth. Since direct measurements are not possible, estimates are generally based on the study of meteorites. Recently, a new technique for probing the Earth's interior was developed in the collaboration between particle physicists and geophysicists and it is based on the detection of so called geo-neutrinos - electron antineutrinos generated within the Earth in radioactive decays of U, Th and K. The designs of the current experiments using scintillating materials and utilizing inverse beta decay (Araki et al. 2005; Chen et al. 2008; Fields et al. 2004: Fiorentini et al.2003; 2005,2007; Fogli et al. 2010) allow the detection of the geo-neutrinos from U and Th decays only. Due to their low energies the anti-neutrinos produced by K require a new detection technique other than presently used liquid scintillation materials. A detailed theoretical analysis of the nuclear processes occurring on an alternative target (cadmium-tungstate crystal ($CdWO_4$)), as well as experimental testing, are still needed to verify the feasibility of this approach.

INTRODUCTION

The deep interior of the Earth is largely unexplored, and significant questions remain regarding the composition and processes of the interior of the Earth and therefore of other terrestrial planets for which the Earth is considered an analog. The deepest drill hole is about 12 km, which penetrates only the Earth's upper crust. Deeper levels of the crust and upper mantle are sparsely sampled by geologic processes. Seismology can reconstruct the density profile throughout the

Earth but not its composition. This lack of knowledge of the deep interior of the Earth results in large uncertainties in Earth's energy production. These uncertainties apply both to the value of heat flow and to the separate contributions to Earth's energy supply (radiogenic, gravitational, chemical, etc.). As a result important questions remain unanswered regarding the dynamics of the deep interior of the Earth and other terrestrial planets.

Precise knowledge of the energy sources in the Earth is of an extreme interest to the entire geosciences community. The total surface heat flux in the Earth is estimated at 44 billion kilowatts. There is a strong belief that the decay of the radioactive uranium (^{238}U) and thorium (^{232}Th) decay chains and potassium (^{40}K) have a major contribution to the terrestrial heat production. The ^{238}U and ^{232}Th currently produce most of the Earth's heat with each contributing roughly equal amounts. ^{40}K is next with an expected input of about half that attributed to either ^{238}U or ^{232}Th.

Recently a new technique for probing the Earth's interior was developed in the collaboration between particle physicists and geophysicists and is based on the detection of so called geo-neutrinos. Geo-neutrinos are the electron antineutrinos generated deep inside Earth in the radioactive decays of ^{238}U, 232Th and ^{40}K via a series of alpha and beta decays:

- $^{238}U \rightarrow {}^{206}Pb + 8\alpha = 6\beta + 6\bar{\nu}_e$
- $^{232}Th \rightarrow {}^{208}Pb + 6\alpha = 4\beta + 4\bar{\nu}_e$
- $^{40}K \rightarrow {}^{40}Ca+\beta+\bar{\nu}_e$ (beta decay, branching ratio 89.28%, Q-value 1.311MeV)
- $^{40}K+e^- \rightarrow {}^{40}Ar+\nu_e$ (electron capture, branching ratio 10.72%, Q-value 1.505MeV).

Their current detection relies on the inverse beta decay, where an antineutrino collides with a proton producing a neutron and a positron (anti-electron)— $\bar{\nu}_e + p \rightarrow e^+ + n$. The positron annihilates with the electron producing two gamma particles and shortly therafter (mean capture time ~200μs) the neutron is captured by a hydrogen nucleus producing deuterium and a 2.2 MeV gamma particle. The detection of this correlated in time and position events allows us to determine a source particle – a geo-neutrino.

Currently there are three major experiments - Borexino at Gran Sasso National Laboratory, Italy; KamLAND in Kamioka mine, Japan and SNO+ in Sudbury, Canada that are using proton-rich scintillating materials and utilizing inverse beta decay with prompt and delayed coincidence to observe the geo-neutrinos (Araki et al. 2005; Chen et al. 2008; Fields et al. 2004: Fiorentini et al. 2003; 2005,2007; Fogli et al. 2010). Current observations of geo-neutrinos at KamLAND and Borexino experiments are very exciting; however, the inverse beta decay process used in all experiments allows us to detect only the neutrinos from ^{238}U and ^{232}Th due to the higher energy threshold of 1.8MeV (Figure 1). Thus, the potassium geo-neutrinos with an energy threshold of 1.311MeV are too low to be detected using this method. The flux of geo-neutrinos from ^{40}K is similar to the flux of geo-neutrinos from ^{238}U and ^{232}Th, yet methods for measuring the ^{40}K geo-neutrino flux do not exist. The currently used experimental methods are not designed for detection of the K-neutrinos, which are of extreme importance because as mentioned earlier, ^{40}K contributes up to 20% of the radiogenic heat production of the Earth's mantle and crust. There is speculation that there might be a non-zero ^{40}K concentration at the core of the Earth that may increase the heat production from ^{40}K decay above 20%. A new technique will require an introduction of different materials than currently used and a large liquid scintillation detector that has yet to be developed to detect the geo-neutrinos from all key radioactive elements including radioactive ^{40}K. We present a new method for detecting geo-neutrinos, results from a prototype detector technology, and a discussion on the detector requirements and sensitivities.

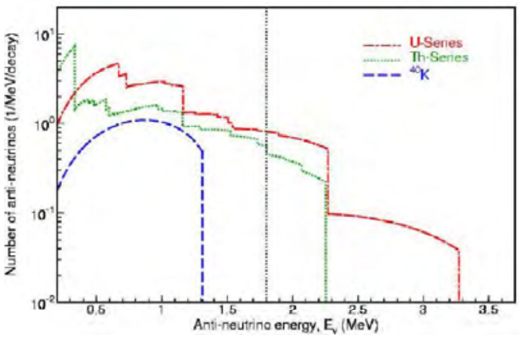

Figure1. The expected ^{238}U, ^{232}Th and ^{40}K decay chain electron antineutrino energy distributions. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to ^{40}K electron antineutrinos (Araki et al 2005).

METHODS

One of the candidates for such an innovative detector would be a cadmium-tungstate ($CdWO_4$) solid state detector, first proposed by Mark Chen () from Queens University in Canada, where the stable cadmium isotope (^{106}Cd) is used as a target. Unfortunately the natural abundance of ^{106}Cd is only 1.25% and enrichment up to 50% or more will be needed.

Similar to the liquid scintillator detectors, the interaction of interest is inverse beta decay, this time on cadmium: $\overline{\nu}_e + {}^{106}Cd \rightarrow {}^{106}Ag + e^+$. This reaction is more suitable for the detection of potassium geo-neutrinos than inverse beta decay in proton reach scintillating material. While the energy of ^{40}K geo-neutrinos can reach 1.311MeV, the inverse beta decay requires energy equal to two electron masses (1.022MeV), which leaves a maximum of 0.289MeV available for the Q-value of the reaction. The Q-value of cadmium (^{106}Cd) → silver (^{106}Ag) is 0.194MeV so the energy threshold of the reaction is 1.216MeV, which is below the maximum value of the ^{40}K geo-neutrino energy. The energy of the positrons produced in this reaction will fall into a 1.02 – 1.12MeV energy range. In this reaction one of two transitions can be seen: $0^+ \rightarrow 1^+$ allowed transition to ^{106}Ag ground state and $0^+ \rightarrow 6^+$ allowed transition to ^{106}Ag first excited state with the excitation energy of 89.66keV. The unstable isotope of silver (^{106}Ag) has a half life of 24min and will transform to stable palladium (^{106}Pd) via two possible processes:

- ~37% - electron capture (EC) - $^{106}Ag + e^{-} \rightarrow {}^{106}Pd + \nu_e$ where:
  - 73% - ^{106}Pd in 0^{+} ground state,
  - 27% - ^{106}Pd in 2^{+} excited state

- ~63% - beta decay (β^{+}) - $^{106}Ag + e^{-} \rightarrow {}^{106}Pd + \nu_e + e^{+}$ where:
  - ~89% - ^{106}Pd in 0^{+} ground state
  - ~11% - ^{106}Pd in 2^{+} excited state

The 511 keV gamma produced in inverse beta decay of cadmium to silver followed by another 511 keV gamma produced by the ^{106}Ag decay to 106Pd in the excited state provides a unique method of detecting potassium geo-neutrinos. The disadvantage of this method is the time separation of 24 min half-life between these two events. This relatively large time window can generate some background events such as random produced positrons in the other beta plus reactions, double beta decay (simultaneously producing two positrons), double electron capture, double beta plus decay, as well as positrons from beta and double beta decays of different cadmium isotopes present in the detector (^{112}Cd, ^{113}Cd, ^{116}Cd, etc (Table 1)). These background events can be minimized if ^{106}Cd of high isotopic purity is used in the construction of the detector. Although the large time separation allows large background, the spatial separation is extremely small. Therefore, the spatial coincidence can be used to reject background.

Table 1. The absolute isotopic composition of naturally occurring cadmium (Belli et al. 2010)

Atomic Number	Enriched ^{106}Cd	Natural cadmium
106	66.407	1.256
108	0.6587	0.893
110	5.067	12.492
111	4.837	12.801
112	8.857	24.132
113	3.9357	12.222
114	8.777	28.734
116	1.4977	7.492

RESULTS

A prototype cadmium detector ($CdWO_4$) was proposed and built using naturally occurring cadmium which is composed of 8 isotopes (Table 1). Decay time calibration and energy resolution was tested using two sizes of the detector (both cylindrical in shape: 9mm and 19mm diameter and 20mm height) and 8 different radioactive sources are listed with their gamma energies:

- ^{109}Cd – 88 keV
- ^{57}Co – 122 keV
- ^{22}Na – 511 keV
- ^{137}Cs – 662 keV
- ^{84}Mg – 834 keV
- ^{60}Co – 1173 keV
- ^{22}Na – 1274 keV
- ^{60}Co – 1333 keV

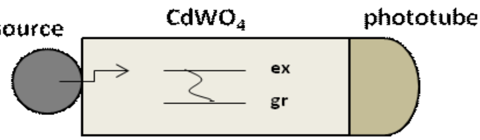

Fig.2 $CdWO_4$ basic setup.

The listed radioactive isotopes produce gamma particles of desired energy (in the range of 88keV to 1.333MeV) that interact with $CdWO_4$ and deposit energy in the crystal. $CdWO_4$ is a high density (7.9 g/cm^3), high atomic number scintillator with relatively high light yield. It emits light at a wavelength of 475 nm, which is visible light, and has a total light yield of about 15 photons/keV. The light yield relative to NaI(Tl) on a Bialkali photomultiplier tube (PMT) can be 50%. The scintillation light inside the CdWO4 transports to the end where it is registered by the phototube placed on the side of the detector (Figure 2).

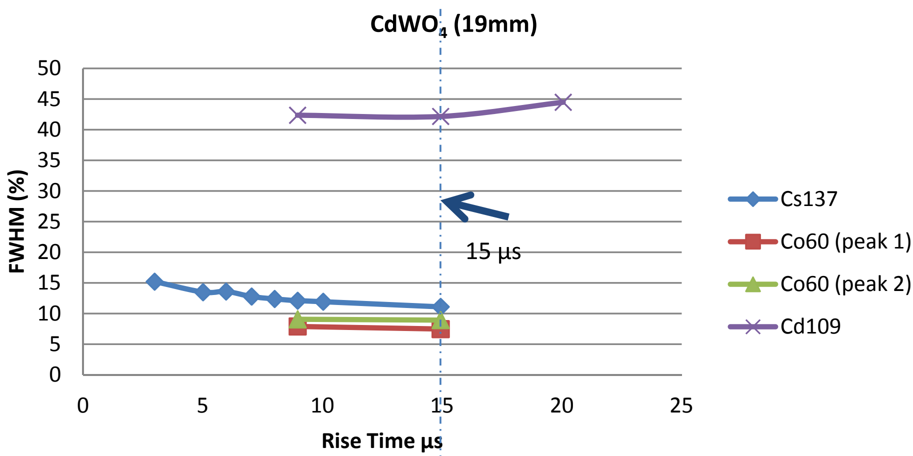

Figure 3. Decay time calibration for $CdWO_4$ detector.

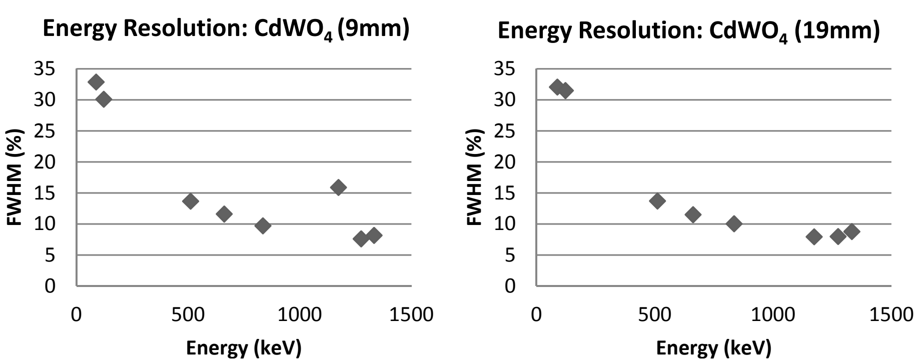

Figure. 4. An energy resolution for $CdWO_4$ detector: 9mm detector on the left panel and 19mm detector on the right panel.

The optimal rise-time (decay time) for the $CdWO_4$ detector was found to be approximately 15μs for different source energies (Figure 3). The energy resolution is extremely important characteristic of any detector. The relative resolution is described by the peak's full width at half maximum (FWHM) divided by the peak center, and multiplied by 100 (FWHM in %). The above description is illustrated in Figure 4. The energy resolution represents the ability of a detector to distinguish between gamma rays of different energies as shown in Figure 5 for 2 gammas from ^{60}Co at 1173keV and 1333keV.

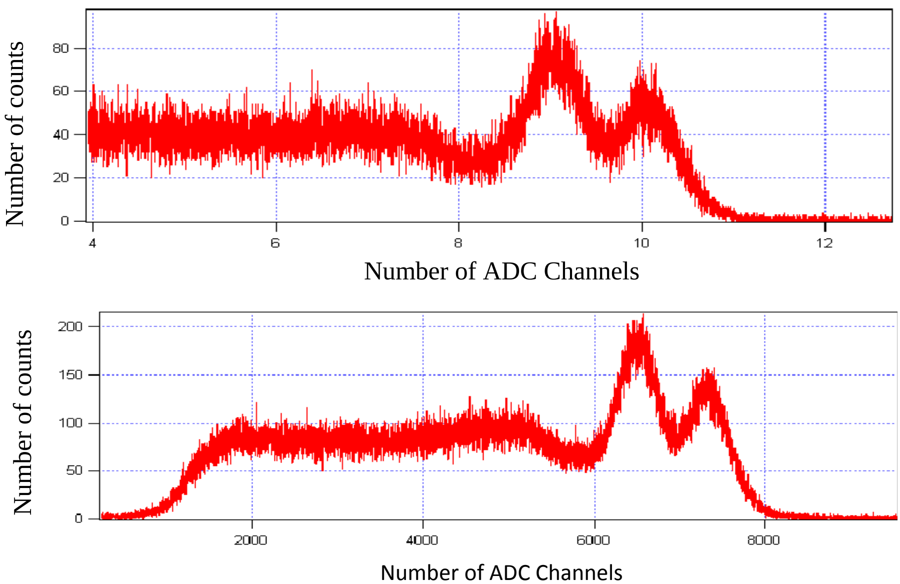

Figure 5. The energy spectrum of the $CdWO_4$ detector demonstrating the resolution of the two gamma lines from the decay of ^{60}Co (upper graph – 9mm detector, lower graph – 19mm detector).

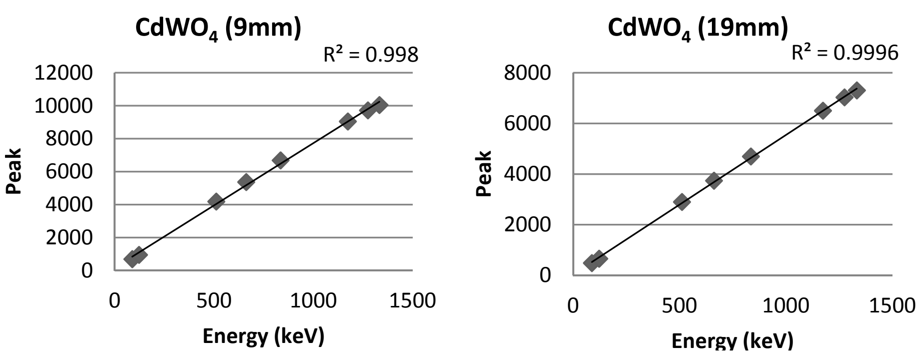

Fig. 6. The correlation between peak location and energy for the $CdWO_4$ crystal (9mm detector on the left and 19mm detector on the right) indicating a highly linear energy response.

The energy response should be linear as can be seen in Figure 6. This is very important to the energy interpretation of an unknown source. Any nonlinear energy response indicates incomplete charge collection by the detector and is an issue that needs to be resolved before good measurement can be done.

The obtained results are used to evaluate the events rate that is necessary to estimate the minimum size of the eventual detector. The size and the possible designs of the $CdWO_4$ detector are still needed to assess the expected cost associated with purchasing the enriched ^{106}Cd, its purification, adequate shielding, photomultipliers, needed software and hardware followed by a determination of the possible underground location of this large scale detector.

DISCUSSION

Two main designs for a cadmium detector are to be considered. One strategy would be to construct a segmented detector. In this design, the candidate events are selected if both signals -the prompt positron with energy equal to that of the electron antineutrino minus 1.216 MeV, and the delayed positron with energy up to 1.943 MeV - originate in the same cell. The 15 μs decay time of CdWO4 exploits this design. The disadvantage of the segmented detector is collecting the scintillation light or placing sensors inside the detector. In both cases there is a potential chance of contaminating the detector with radioactivity and increasing background.

Another strategy is a monolithic detector with sensors on the outside looking inward and isolating radioactivity from the scintillator by a buffer layer (the method used in KamLAND and Borexino experiments). In this case the decay time can be shifted from the microsecond to the nanosecond timescale using a dopant method when growing the crystals. With a fast scintillator, the timing of the sensor signals can be used to resolve the position of the source of the scintillation light. Both designs have to be carefully analyzed in the near future.

The low energy threshold (1.311 MeV) of ^{106}Cd makes it a perfect candidate for the K geo-neutrino detector. The extremely rare interactions between the antineutrinos and the proposed target are expected to produce only a couple of events/ton/year. Estimating the size of the detector requires the reevaluation of the precise anti-neutrino – ^{106}Cd cross sections at low anti-neutrino energies (~1.2-1.3 MeV) and the number of expected events. In order to obtain accurate results for the matrix element and cross section, we must study the nuclear structure of cadmium and determine with the highest accuracy a nuclear matrix element for the desired reaction. Based on this, we can determine the theoretical input, the size and the design of the detector, an estimate of the cadmium enrichment, and the material purity. The entire geosciences community is awaiting new progress related to the feasibility of the $CdWO_4$ detector and the development of techniques for detecting K geo-neutrinos.

The detection of the geo-neutrinos from the U, Th and K decays in the Earth is needed to explain the sources of the terrestrial heat flow and the quantity and distribution of radioactive elements internally heating the Earth. Radiogenic heating helps power plate tectonics, hot spot volcanism, mantle convection, and possibly the geo-dynamo. Information on the extent and location of this heating better defines the thermal dynamics and chemical composition of Earth. Whereas U and Th dominantly determine the most recent thermal evolution of Earth, it is K and U that hold this distinction during the first billion years of Earth history (Anderson 1989). Thus, an understanding of Earth's entire thermal evolution history requires a complete U, Th and K budget. Geo-neutrino observation can provide access to this knowledge provided methods for measuring K geo-neutrinos can be developed.

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