Basics of Analysis with Antineutrinos From Heat Producing Elements - K, U, Th in the Earth

IAP 2010, January 5 - 22

Earth, Atmospheric & Planetary Sciences

Massachusetts Institute of Technology

Session 4: January 21, 2010, 10 AM to Noon

Instructor *Dr. Ila Pillalamarri*

Course **12.091 Special Topics in Earth Sciences**

Course Objectives

1) Relevance to antineutrino analysis of global concentration determination of radiogenic heat producing elements (HPE) by terrestrial heat flow studies and Bulk Silicate Earth (BSE) models, and unconventional models of the Earth's core.

2) Basic radiation characteristics of heat producing elements (HPE):

Alpha, beta, gamma, neutrino and antineutrino radiations,

Basics of radiation detection concepts,

Special focus:

Antineutrino radiation detection,

Antineutrino radiation detection with directional sensitivity.

Course Objectives Continued

3) Relevance of existing large antineutrino detectors for probing the HPE in Earth's deep interior:

   Characteristics, research and contributions of the two existing antineutrino detectors – Sudbury Neutrino Observatory (SNO), Canada and Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Japan.

4) Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity. Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth. Need for mobile antineutrino detectors for tomography.

5) Considerations for dedicated antineutrino detectors to probe the Earth's deep interior for the determination of concentrations of heat producing elements.

Course Schedule
January 5 – 22, 2010

Jan 05: Room 54-312

Relevance to antineutrino analysis of global concentration determination of radiogenic heat producing elements (HPE) by terrestrial heat flow studies and Bulk Silicate Earth (BSE) models, and unconventional models of the Earth's core.

Jan 19: Room 54-312

Basic radiation characteristics of heat producing elements (HPE):

Alpha, beta, gamma, neutrino and antineutrino radiations,

^{40}K decay characteristics, U and Th decay series

Basics of radiation detection concepts,

Special focus:

Antineutrino radiation detection,

Antineutrino radiation detection with directional sensitivity.

Course Schedule
January 5 – 22, 2010

Jan 20: Room 54-312

Relevance of existing large antineutrino detectors for probing the HPE in Earth's deep interior:

Characteristics, research and contributions of the two existing antineutrino detectors – Sudbury Neutrino Observatory (SNO), Canada and Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Ja pan.

Jan 21: Room 54-312

Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity. Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth. Need for mobile antineutrino detectors for tomography.

Visit to Earth Atmospheric & Planetary Sciences – Radiometric/Neutron Activation Analysis Laboratory (NW13-263).

Jan 22: Room 54-312

Considerations for dedicated antineutrino detectors to probe the Earth's deep interior for the determination of concentrations of heat producing elements.

Conclusions.

Student Presentations.

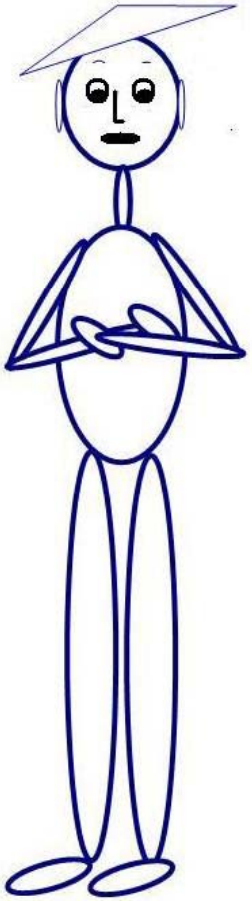
Details of course work

The course work involves the following:

1.	Class attendance and participation	25%
2.	Reading assignments	25%
3.	Homework assignments	15%
4.	Student report	15%
5.	Student presentation	15%

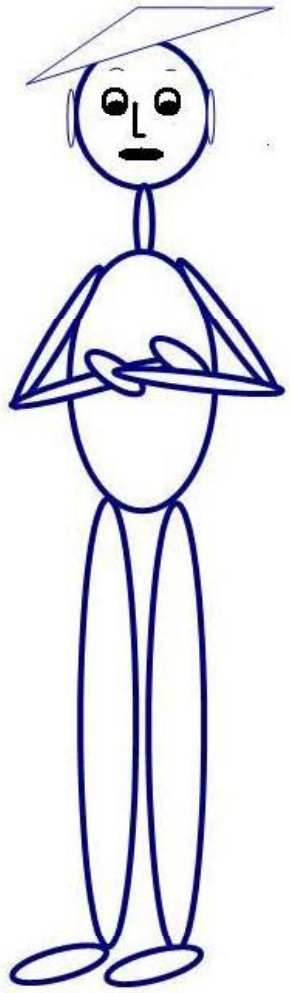
Required percentage to pass this course is 95%.

Course Overview



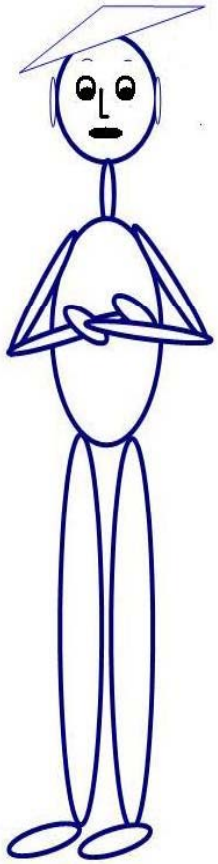
- Basics of
  - Analysis with
    - Antineutrinos from
      - Heat Producing Elements K, U, Th
        - In the Earth

Session Objectives



- Proposed antineutrino detectors for probing the HPE in Earth's deep interior with directional sensitivity.
- Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth.
- Need for mobile antineutrino detectors for tomography.

Next proceeding to



Some antineutrino detectors, recently proposed for probing the HPE in Earth's deep interior

SNO+
BOREXINO
HANO (DOANO)
BNO

Antineutrino Detectors @ Continents & Oceans

- Practical antineutrino detectors were designed and tested for specific purposes for over fifty years.
- The first successful detector design demonstrated the detection principle by inverse beta decay.
- Powerful detectors are already built – SNO to study solar neutrinos, BOREXINO to study low Energy solar neutrinos, KamLAND to study neutrino oscillations from fission antineutrino sources, studying the Earth's antineutrinos with the same experimental setup.

Antineutrino Detectors @ Continents & Oceans

- Antineutrino detectors located at different sites, by being on continental crust and at the interface to an oceanic crust, are expected to provide perspectives of distribution of U-Th in the Earth's crust and mantle.
- Currently, there is strong interest to use the existing detectors initially built for physics studies, now to study the antineutrinos originating from the Earth to investigate the K, U, Th in deep interior of the Earth.

Antineutrino Detectors @ Continents & Oceans

- KamLAND already in operation, is the first antineutrino detector to study antineutrinos from the Earth.
- SNO will be modified to SNO+ to study Earth's antineutrinos.
- BOREXINO is in preparation to study Earth's antineutrinos.
- Hanohano is in preparation to study Earth's antineutrinos.

Antineutrino Detectors @ Continents & Oceans

SNO+

- SNO+ is a proposed follow-up experiment to SNO. By replacing the heavy water in SNO with liquid scintillator, the SNO+ detector would be sensitive to lower energy antineutrinos generated in the Earth.

http://snoplus.phy.queensu.ca/about.html

http://snoplus.phy.queensu.ca/images.html

Antineutrino Detectors @ Continents & Oceans

SNO+

- SNO+ antineutrino signal dominated by continental crust; checks basic geochemical ideas about the crust
- SNO+ and the local geology
  - Canadian Shield (also known as the North American Craton)
    - old, thick, well-understood continental crust
    - mining activities near Sudbury suggest that the very local geology is extremely well studied
- SNO+ proposal is that constraining the local U, Th content in the surrounding rocks, it is possible to infer the mantle component in the SNO+ antineutrino signal. By subtracting off from the total signal the mantle component may be obtained, assuming core component to be insignificant.

  http://www.ipp.ca/pdfs/SNOp_chen.pdf

Antineutrino Detectors @ Continents & Oceans

BOREXINO

- Borexino is acronym for BORon Experiment. The project first detected solar neutrinos on 16 August 2007. The experiment is located at the Laboratori Nazionali del Gran Sasso near the town of L'Aquila, Italy.
  http://borex.lngs.infn.it/
- Borexino is predominantly a particle physics experiment to study low energy (sub MeV) solar neutrinos.
- For A detailed description of the detector refer
  Nuclear Instrumentation and Methods A,
  ARXIV.ORG/ABS/PHYSICS/0702162
- Other goals of the experiment are detecting Boron-8, pp, pep and CNO solar neutrinos as well as antineutrinos from the Earth and nuclear power plants.
- Thus BOREXINO is not a dedicated antineutrino detector for solely measuring the HPE concentrations from different shells of the Earth.

Antineutrino Detectors @ Continents & Oceans

Deep Ocean Anti Neutrino Observatory (DOANO)
Hawaii Anti Neutrino Observatory - Hanohano

Hanohano is a deep ocean antineutrino observatory being developed at Hawaii. The 10 kT antineutrino detector is expected to be mobile, to be towed from place to place away from or near to nuclear reactors on the Earth.

A one-year deployment near Hawaii is expected to measure the flux of Th/U geo-neutrinos from the mantle to 25%.

An exposure of four years is expected to measure the Th/U ratio to 10%.

Expected to measure or severely constrain the power of the hypothetical nuclear reactor at the center of the Earth's core.

Ref.

http://neutrinos.llnl.gov/workshop/presentations/22_Learned.ppt

http://cdsweb.cern.ch/record/1000480/files/0611039.pdf?version=1

Antineutrino Detectors @ Continents & Oceans

Low Energy Neutrino Astrophysics LENA

- Proposed LENA detector
- BOREXINO technology
- Liquid scintillator 45,000 ton PXE
- Cylindrical detector

  100 m length x 30 m diameter
- Photomultipliers 12,000 with 30% surface
- Possible locations

  Pyhasalmi, Pylos
- Propose to probe the Earth's deep interior on the basis of the angular dependence of the geoneutrino flux.

Ref.: Probing the Earth's interior with the LENA detector
http://arxiv.org/PS_cache/hep-ph/pdf/0610/0610048v1.pdf

Antineutrino Detectors @ Continents & Oceans

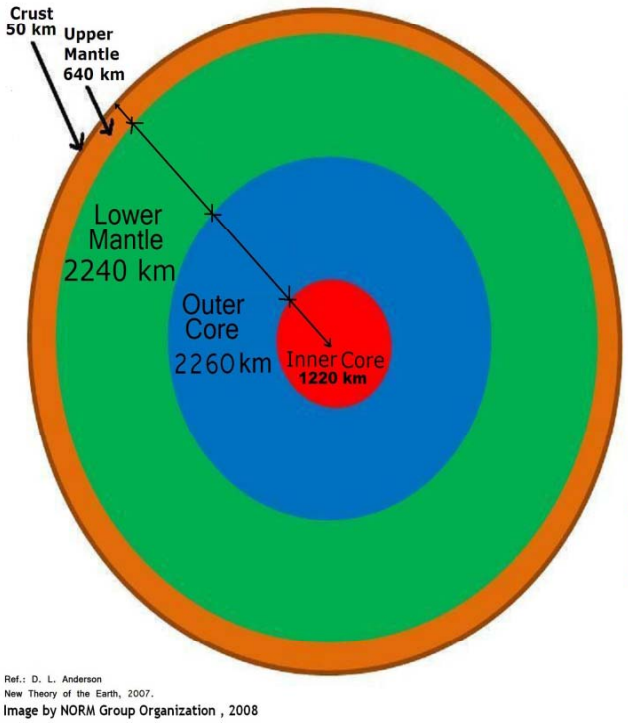
Antineutrino signal of K, U, Th, whether the antineutrino detector is located on continent or in ocean, should

1) Identify K, U, Th uniquely, free of interferences

2) Measure K, U, Th abundances, totally for the entire Earth, and also individually for crust, mantle and core.

Directional detection sensitivity is required for independent measurements.

Earth Shells



Regions	Radial Thickness km
Crust	50
Upper Mantle	640
Lower Mantle	2240
Outer Core	2260
Inner Core	1220

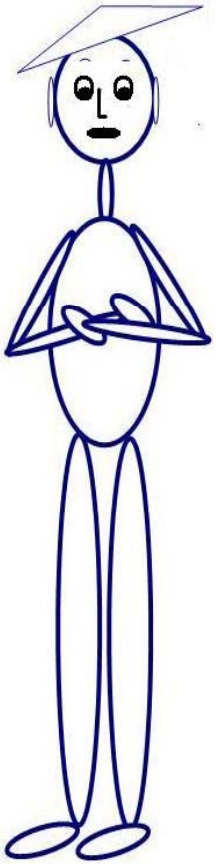
Image courtesy of NORM Group Organization
Used with permission

- The individual HPE concentrations in different shells of the Earth are unknown so far.
- Total concentration of the entire Earth is also unknown so far.
- Measurement of the HPE concentrations in each Earth shell can be achieved by preserving the direction of the incident antineutrinos.

Some Antineutrino Detectors @ Continents & Oceans

Detector	Region	Location	Detector Size Kilo Tonnes
Borexino	Italy	Tunnel Continental Crust	0.1
KamLAND	Japan	Mine Island Arc	1
SNO+	Canada	Mine Continental Crust	1
Hanohano	Pacific Ocean	Ocean Oceanic Crust	10
Baksan	Baksan	Continental Crust	30
LENA	Finland	Continental Crust	50
EARTH	Tomography		
GRAFG	Radiometric Analysis		

Next proceeding to



Antineutrino detection with incident directional sensitivity:

Simulation studies of angular radial distribution of K, U, Th in the Earth

Tomography of the whole Earth for the localization of the HPE in the deep interior of the Earth:

EARTH proposal

GRAFG proposal

Angular Directions Simulation Studies

Theoretical simulation studies performed by Fields and Hochmuth [2004]:

- Ref.: **Imaging the Earth's Interior: the Angular Distribution of Terrestrial Neutrinos**
- Importance of Imaging the Earth's Interior with the Angular Distribution of antineutrinos from different shells prospects regarding antineutrino directional sensitivity was theorized by Fields and Hochmuth.
- The angular distribution of geoneutrinos are calculated, which opens a window on the differential radial distribution of terrestrial radionuclides. General formalism is developed for the neutrino angular distribution.
- Inverse transformation is presented which recovers the terrestrial radioisotope distribution given a measurement of the neutrino angular distribution.
- Thus, geoneutrinos not only allow a means to image the Earth's interior, but offering a direct measure of the radioactive Earth, both
- (1) revealing the Earth's inner structure as probed by radionuclides, and
- (2) allowing for a complete determination of the radioactive heat generation as a function of radius.

Earth AntineutRino TomograpHy Project EarTH

- EARTH collaboration led by Prof. R. J. De Meijer proposed tomography of the Earth by antineutrino telescopes.
- The aim of EARTH (Earth AntineutRino TomograpHy) is to map radiogenic heat sources in the Earth's Interior with ultimately an angular resolution of about 3 degrees.

Earth AntineutRino TomograpHy

EarTH Project

According to De Meijer et al:

- The CMB is a very dynamic part of the Earth. It is a thin (~200km thick) interface between the core and the mantle
- Due to subduction of crust and oceanic magma the CMB may contain 40% of the Earth radionuclides and hence radiogenic heat sources.
- Mapping of these heat sources therefore requires high resolution (~3˚) antineutrino tomography.

Earth AntineutRino TomograpHy Project

EarTH

According to the EARTH proposal:

- The first antenna is planned to be installed at Curacao, Dutch Antilles.
  Antennas are designed to contain a mass of about 4 kilotonnes of solid scintillation material.
- Contrary to the KamLAND detector or the ones planned for Borexino, LENA, Hawaii, or Baksan, all monolithic, spherical arrangements.
- The EARTH antennas will be modular and will consist of many modules, each containing a large number of rod-shaped detector units, containing small sized detectors, thus angular resolution can be achieved.

Earth AntineutRino TomograpHy

EarTH Project

The Earth AntineutRino TomograpHy programme aims at making a tomographic image of the radiogenic heat sources in the Earth's interior by a system of ten geoneutrino telescopes with a combined angular resolution of 3°.

Anticipated spatial resolution dimension is ~3°, corresponding to about 300km for the centre of the Earth; 150 km at the CMB.

Each telescope will contain 4 ktonnes of detection material and will have at least 10 antennas consisting of many modules.

Earth AntineutRino TomograpHy

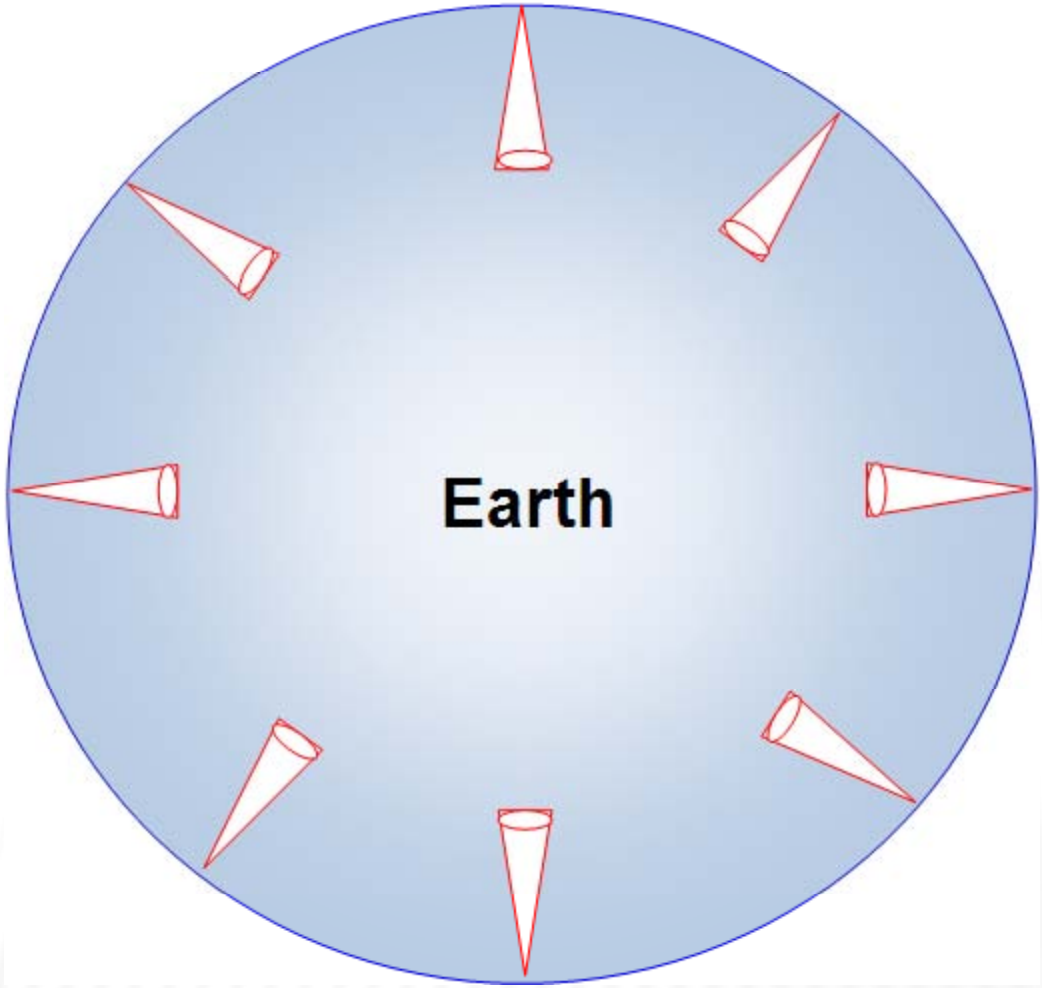
EarTH Project

Detector Dimensions

- Each EARTH telescope is designed to have 4kton of scintillator: three times the mass of KamLAND.
- With 4cm^2 diameter, 1m long detectors, 10 million detector units are required!
- Ten telescopes comprise a mass of 40kton: twice Superkamiokande

Earth AntineutRino TomograpHy

EarTH Project



Meter cubed antineutrino detector

- Antineutrino detectors could be simpler to construct and operate than the current generation of detectors, which were built to investigate the basic physics of the neutrinos.
- Bernstein et al [2008] and earlier Klimov et al [1994] showed the potential use of Cubic-meter-sized antineutrino detector for monitoring non intrusively, robustly, and automatically, and safeguard a wide variety of nuclear reactor types, including power reactors, research reactors, and plutonium production reactors.
- Ref.
- Y. V. Klimov, V. Kopeikin, L. Mikaelyan, K. Ozerov, and V. Sinev,
  Atomic Energy, 1994, 76, 130.
- A. Bernstein, N. S. Bowden, A. Misner, and T. Palmer,
  Monitoring the thermal power of nuclear reactors with a prototype cubic meter antineutrino detector
  Journal of Applied Physics, 2008, Vol. 103, 074905-1 to 074905-10
  DOI: 10.1063/1.2899178

Meter cubed antineutrino detector

Meter cubed antineutrino detector diagram can be seen in the following references.

- A. Bernstein, N. S. Bowden, A. Misner, and T. Palmer,
  Monitoring the thermal power of nuclear reactors with a prototype cubic meter antineutrino detector,
  Journal of Applied Physics, 2008, Vol. 103, 074905-1 to 074905-10.
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- A. Bernstein,Y. Wang, G. Gratta, T. West
  Nuclear reactor safeguards and monitoring with antineutrino detectors
  Journal of Applied Physics, 2002, Vol. 91 (7) 4672 - 4676.
  http://arxiv.org/ftp/nucl-ex/papers/0108/0108001.pdf
- N.S. Bowden, A. Bernstein, M. Allen, J.S. Brennan, M. Cunningham, J.K. Estrada, C.M.R. Greaves, C. Hagmann, J. Lund, W. Mengesha, T.D. Weinbeck, C.D. Winant
  Experimental results$_f$ rom an antineutrino$_d$ etector$_f$ or cooperative monitoring of nuclear reactors
  Nuclear Instruments and Methods in Physics Research A 572 (2007) 985–998.
- Y. V. Klimov, V. Kopeikin, L. Mikaelyan, K. Ozerov, and V. Sinev,
  Atomic Energy. 1994, 76, 130.

GRAFG

GRAFG is an acronym for

Geoneutrino Radiometric Analysis for Geosciences

The GRAFG collaboration, during 2008 - 2009, for Deep Underground Science and Engineering Laboratory (DUSEL) Initial Suite of Experiments, proposed the following.

1) Antineutrino radiometric determination of K, U, Th abundances, independent of geophysical or geochemical models.
2) Use of cubic meter sized antineutrino detectors in modular form, with directional sensitivity.
3) Tomography of Earth's shells by developing directional sensitivity for antineutrino analysis by Cherenkov radiation methodology
4) Initially determine the total global radioactivity of the entire Earth which is cost and time effective.
5) Do not assume insignificant radioactivity contribution from the core of the Earth.

Ref.:

http://www.dusel.org/PDFs/dedc/july2008/DUSEL_Project_Update_July_2008_GRAFG-ILA.ppt

GRAFG

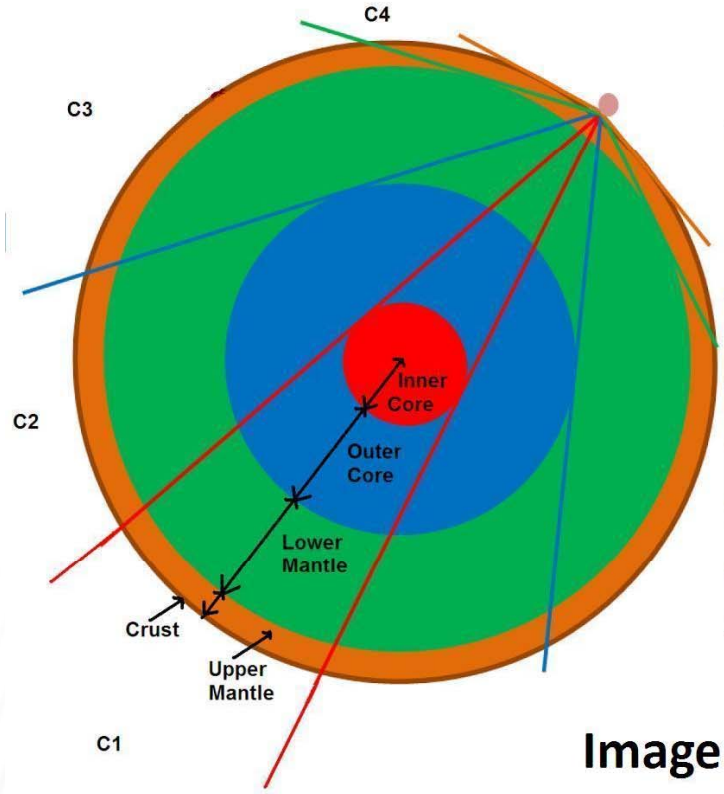
Radiometric analysis in general means measurement of source strengths of the elements from their radio-isotopes.

Geoneutrino radiometric analysis is analogous to the well known gamma-ray radiometric analysis of K, Th , U to measure the concentrations of K, Th, U in (rock) samples.

In the present context, geoneutrinos are used instead of gamma-rays.

Source strengths are used for radiometric analysis.

GRAFG



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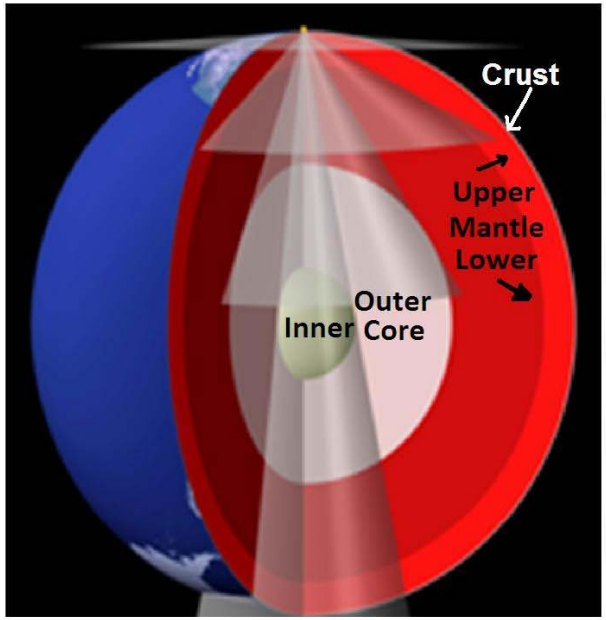

Image Courtesy of The NORM Group Organization

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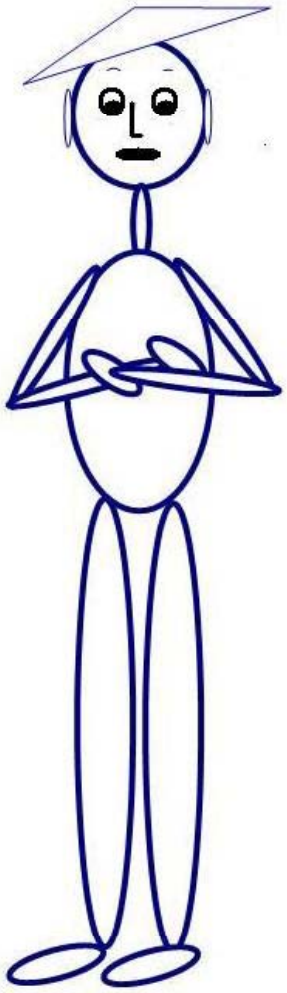
Figure. Cross-sectional schematic of the conical field of view dividing the interior regions of the Earth from the detection point of view.
The cones C1, C2, C3, C4 completely enclose the inner core, outer core, lower mantle, upper mantle regions in the interior of the Earth. - GRAFG

Session Overview



- Talked about the proposed antineutrino detectors
  - SNO+
  - BOREXINO
  - Hanohano
  - Baksan

  for probing the HPE in Earth's deep interior .

- Talked about the proposed antineutrino detector for tomopraphy of the whole Earth for the localization of the HPE in the deep interior of the Earth.
  - EARTH
  - GRAFG

- Talked about need for mobile antineutrino detectors for tomography
  - Meter cubed detector
  - GRAFG

Session 4 : Student Assignments
January 21, 2010

1. Write a report about your understanding of analysis with antineutrinos from heat producing elements – K, U, Th in the Earth.
2. Write a report about your understanding of different antineutrino detectors.

   The report should be about 1 - 2 pages.

References

Directional sensitivity for detection of Earth's Antineutrinos

- B. D. Fields and K. A. Hochmuth

  Imaging the Earth's Interior: the Angular Distribution of Terrestrial Neutrinos

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  (31 May 2004)

- Domogatsky, G., Kopeikin, V., Mikaelyan, L., Sinev, V.,

  Can Radiogenic Heat Sources Inside the Earth be located by their Antineutrino incoming Directions?,

  Phys. Atom. Nucl. 69 (2006) 1894 - 1898,

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  http://borex.lngs.infn.it/

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  Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
  Volume 600, Issue 3, 11 March 2009, Pages 568-593
  http://bryza.if.uj.edu.pl/zdfk/wp-includes/publications/borexino_detector_2009.pdf

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Low Energy Neutrino Astrophysics detector

Probing the Earth's interior with the LENA detector

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Meter cubed antineutrino detector

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  Atomic Energy. 1994, 76, 130.

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SNO+

http://www.ipp.ca/pdfs/SNOp_chen.pdf

http://snoplus.phy.queensu.ca/about.html

http://snoplus.phy.queensu.ca/images.html

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END of Fourth SESSION

12.091 Basics of Analysis with Antineutrinos from Heat Producing Elements – K, U, Th in the Earth

January (IAP) 2010