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 3: January 20, 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.

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:

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

Student Presentations

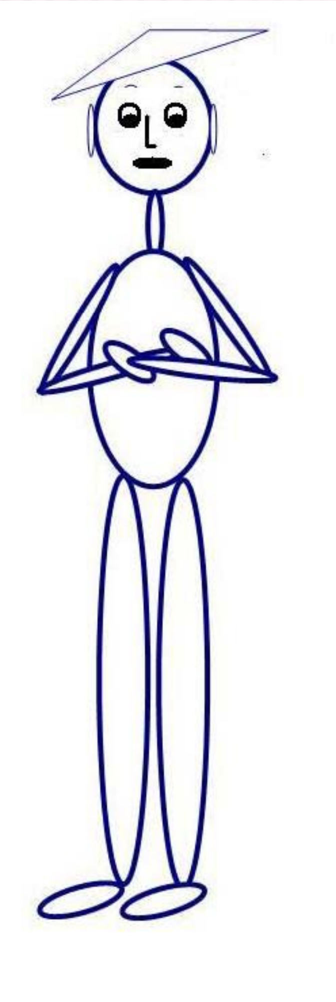
Details of course work

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%

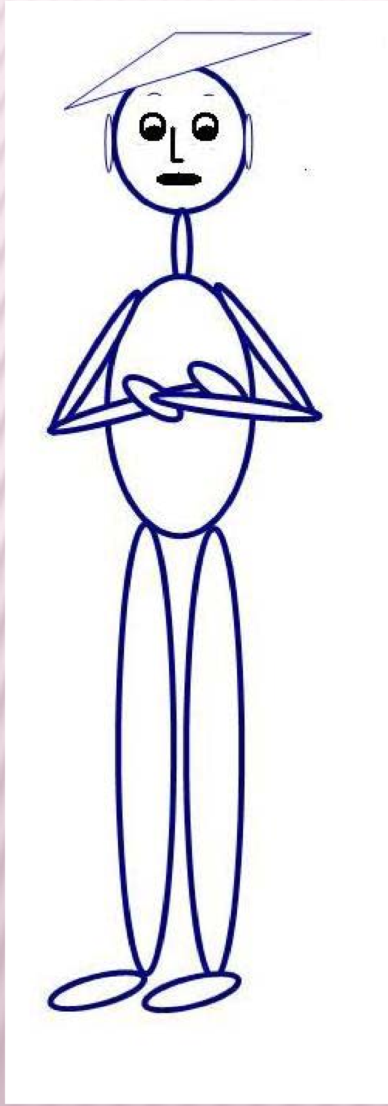
Required percentage to pass this course is 95%.

Course Overview



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

Session Objectives



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

Characteristic features of the two existing antineutrino detectors –

- Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), Japan.
- Sudbury Neutrino Observatory (SNO), Canada.

Antineutrino Detection As Probing Tool

Well established fact is that the heat produced in the interior of the Earth from alpha-, beta- radioactivity may be measurable by detecting antineutrinos from the beta decays.

Essentially, all the antineutrinos reach the surface of the Earth, without attenuation of the emitted intensity unlike alpha, beta and gamma rays, so that the whole Earth can be sampled.

Ref. Eder (1966) and Marx (1960, 1969)

Antineutrino Detection As Probing Tool

U and Th abundances and their distributions in the entire Earth are not known, except for a thin layer near the surface where direct sampling is possible.

Well known Bulk Silicate Earth (BSE) model and geochemical arguments distribute U and Th masses mainly between the continental crust and the lower Mantle. and thus the geoneutrino flux is expected to vary with geographical position of the observational point, decreasing from continental to oceanic sites. Ref. R. Raghavan et al 1998.

Antineutrino signal – Earth's Shells

- Antineutrino signal from Crust.
- Antineutrino signal from Mantle.
- Antineutrino signal from Core.
- They are of interest separately.
- They are not measured so far by direct methods.

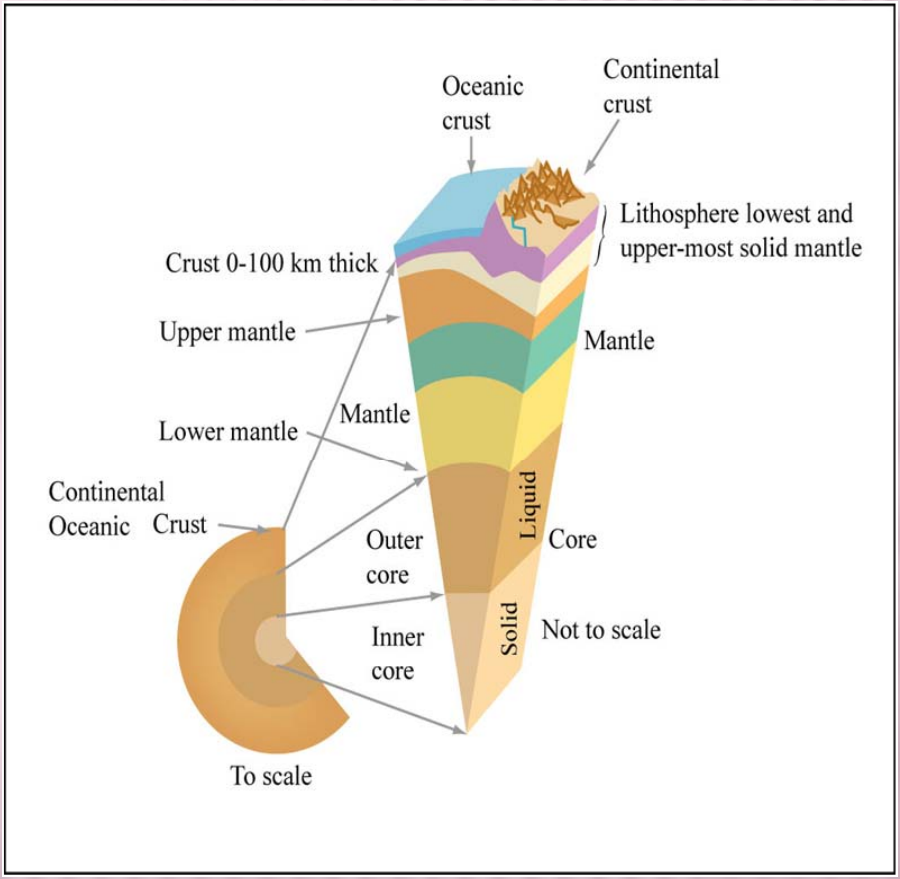


Image by MIT OpenCourseWare

Antineutrino Detectors @ Continents & Oceans

- Two massive liquid scintillation detectors are built -
- 1. Borexino on continental crust

  2. KamLAND on oceanic crust.
- These two sites in particular, one being on a continental crust and the other at the interface to an oceanic crust, are expected to bring unanticipated perspectives for probing the distribution of U-Th in the Earth's crust.
- There have been proposals that detectors stationed at appropriate geographical sites can separate the crust and mantle contributions, thereby to confirm or discard predictions of the Earth's model.
- Earlier proposals -

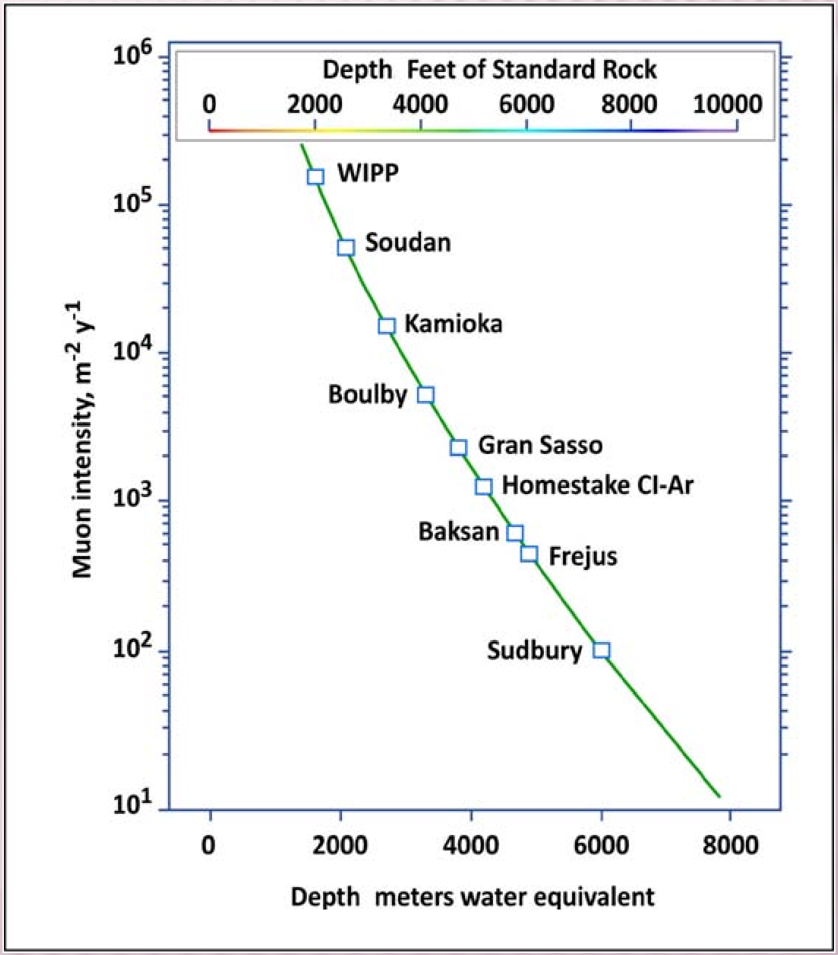
  Ref. Rothschild et al, Raghavan et al, Fiorentini et al, Domogatsky et al

Antineutrino Detection As Probing Tool

- For the methods proposed towards this goal in the last 30 years [Ref. Avilez, Krauss, Kobayashi and Fukao, Domogatsky], the most practical is the inverse beta-decay reaction on the protons in a liquid scintillator.
- The measured antineutrino flux yields the abundance of K, U, Th (HPE) in the whole Earth.

Cosmic ray Intensity reduction with depth

- Antineutrino detectors are usually operated underground in order to reduce the cosmic –ray background interference.
- The figure shows the reduction in cosmic-ray intensity with depth from the surface of the Earth.
- For example the cosmic background at Gran Sasso at a depth of about 5000' is a factor of 10 less than at Kamioka located at about 3500' deep below the surface.



Existing Antineutrino Detectors & Some Proposed Antineutrino Detectors

Project Name		Location
KamLAND	**Existing**	**Kamioka, Japan**
SNO	**Existing**	**Sudbury, Canada**
BOREXINO	**Existing**	**Italy**
SNO+	**Proposed**	**Sudbury, Canada**
DOANO	**Proposed**	**Hanohano, Pacific Ocean**
EARTH	**Proposed**	
LENA	**Proposed**	
GRAFG	**Proposed**	**USA**

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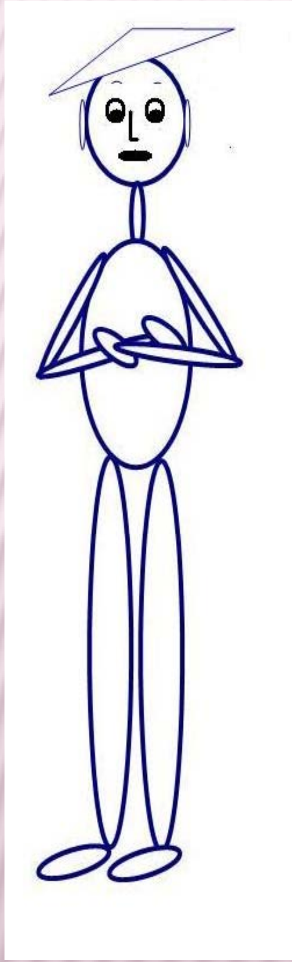


Existing antineutrino detector

- KamLAND
  Kamioka mine, Hida, Japan
- This was built for studying properties of antineutrinos produced bypower reactors from fission of U.

KamLAND Antineutrino Detector

KamLAND stands for

Kamioka

Liquid-scintillator Anti-Neutrino Detector

http://www.awa.tohoku.ac.jp/KamLAND/

KamLAND Antineutrino Detector Location

KamLAND is located in the Kamioka mine, 1,000 m below the summit of Mt. Ikenoyama, Gifu prefecture, Hida, Japan.

GPS: 36° 25' 35.562'' N, 137° 18' 43.495" E.

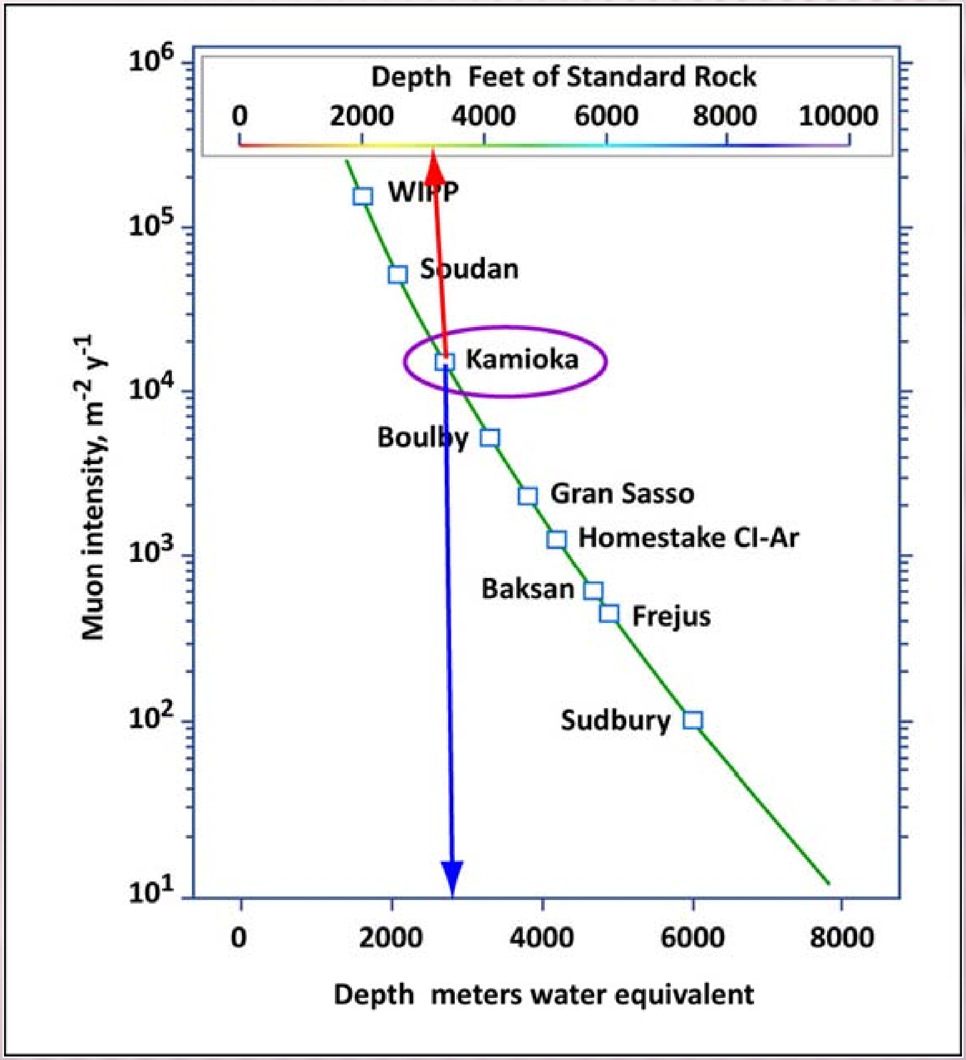
Reference:

http://www.awa.tohoku.ac.jp/KamLAND/

http://www.awa.tohoku.ac.jp/KamLAND/kamland_03a-e.html

Cosmic ray Intensity reduction with depth
KamLAND Detector Location

Located in Kamioka mine, under the mountain.
Altitude of is 358 m,
Rock overburden
2,700 meter-water-equivalent mountain rock under
Mt. Ikenoyama (1368 m),
About 1000 m below summit



http://www.awa.tohoku.ac.jp/KamLAND/News/English/intl-conference/data/Pro-inoue/NOW2004proc.pdf

KamLAND Antineutrino Detector Details

Liquid Scintillator 1000 tonnes
Mainly consists of only C and H
Fiducial volume 408 tonnes
Detector medium container plastic balloon

Surrounded by
Photo Multiplier Tubes (PMT)

17-inch PMT 1325
20-inch 554
Efficiency 68.7%

Yields light on ionization
(8000 photons / MeV)
http://kamland.stanford.edu/Pictures/Pictures.html
http://kamland.lbl.gov/Pictures/

KamLAND Antineutrino Detector Schematic

http://kamland.stanford.edu/Pictures/Pictures.html

http://kamland.lbl.gov/Pictures/

KamLAND Antineutrino Detector Details

- KamLAND consists of an 18 m diameter stainless steel spherical vessel
- 1879 photomultiplier tubes are mounted on the inner surface of the vessel.
- Inside the sphere is a 13 m diameter nylon balloon filled with liquid scintillator.
- The scintillator consists of 1,000 tons of mineral oil, benzene and fluorescent chemicals.

KamLAND Antineutrino Detector Details

The KamLAND Liquid Scintillator consists of

80 v% of normal-Dodecane

+ 20 v% of Pseudocumene

+ 1.52 g/liter of PPO (2,5-Diphenyloxazole)

where, v% stands for % in volume.

PPO is a flour widely used in large scale liquid scintillators.

Figure for molecular structure of these chemicals

Reference:

Suekane, F, T. Iwamoto, H. Ogawa,
An Overview of the KamLAND 1-kiloton Liquid Scintillator
http://arxiv.org/ftp/physics/papers/0404/0404071.pdf

Antineutrino Detection by Inverse Beta Decay Reaction

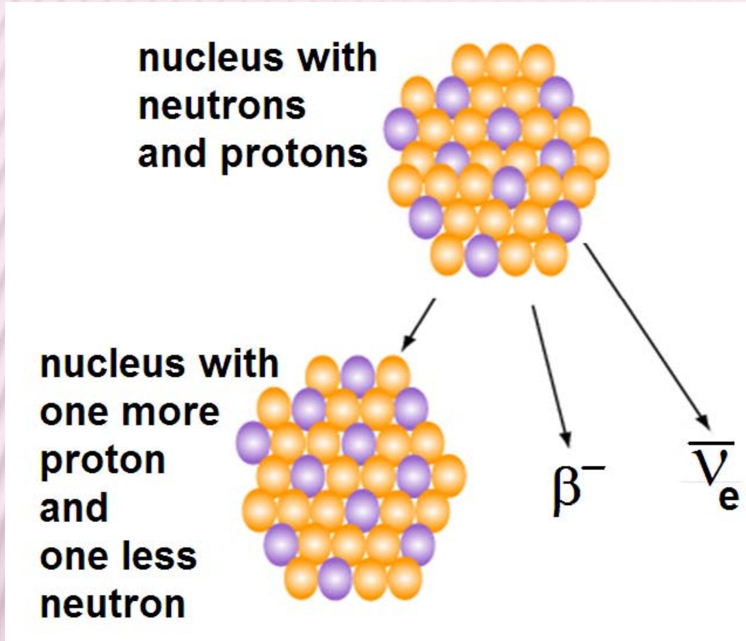


Image by MIT OpenCourseWare

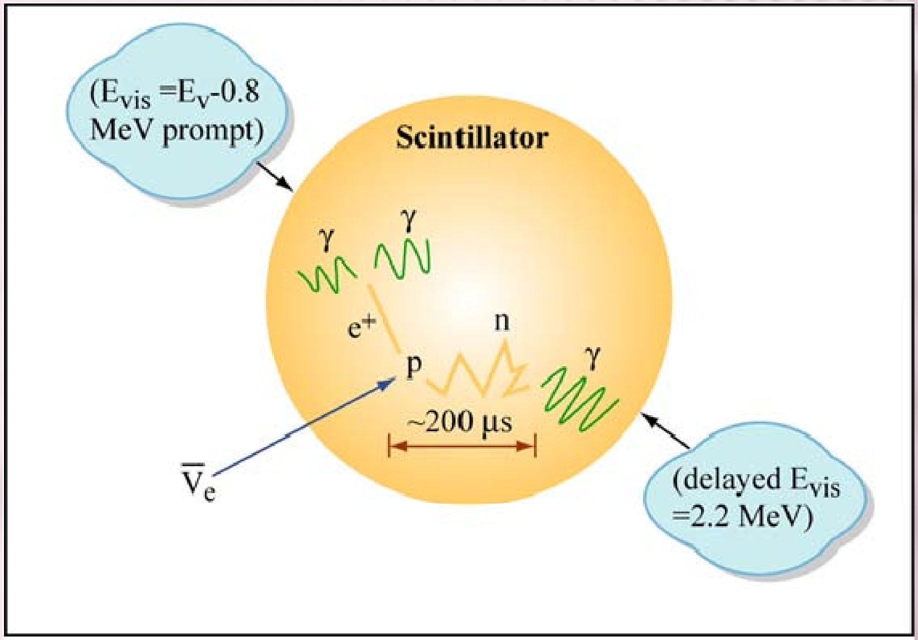


Figure. Antineutrino detection by inverse beta decay reaction

- **E_ν > 1.8 MeV**
- **Information of direction of the incident antineutrino will be lost in the detection process by scintillation reaction mechanism.**

Detecting AntiNeutrinos

- Inverse beta reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Delayed coincidence signal
  - neutron capture: 2.2 MeV γ, t = 0.2 ms
- Reaction threshold: 1.8 MeV
- Natural isotopes with Q_β > 1.8 MeV
  - ^{214}Bi, ^{234}Pa (U chain)
  - ^{228}Ac, ^{212}Bi (Th chain)

KamLAND Antineutrino Detector
Earth's Antineutrino Studies

References:

Experimental investigation of geologically produced antineutrinos with KamLAND

KamLAND Collaboration,

Nature 436, 499-503 (28 July 2005) | doi:10.1038

http://www.nature.com/nature/journal/v436/n7050/abs/nature03980.html

KamLAND Antineutrino Detector
Relevance to Analysis of HPE in the Earth

- KamLAND is the first to determine the antineutrinos from the Earth's HPE
- KamLAND does not have directional sensitivity of the incident antineutrinos arising from the HPE, at the site of interaction in the detector medium. This information will be lost due to inverse beta decay interaction.
- Proximity to about 180 nuclear reactors leads to lower sensitivity to the analysis of HPE in the Earth.
- It is not dedicated to the Analysis of HPE in the Earth. It is designed for neutrino oscillations experiments.
- Its analysis is model dependent. It does not provide independent determination of HPE for the global radioactivity of the Earth.
- It is not mobile. It does not have tomographic capability.

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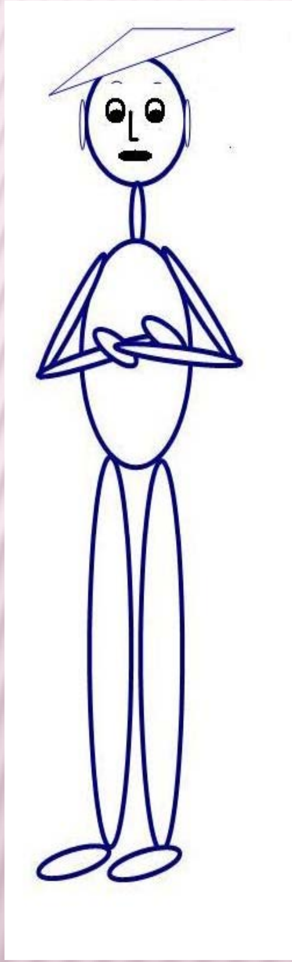


Existing antineutrino detector –

- Sudbury Neutrino Observatory SNO, Sudbury, Canada
- Built for Solar neutrino studies Has directional sensitivity This is a Cherenkov detector Not a scintillation detector unlike KamLAND.

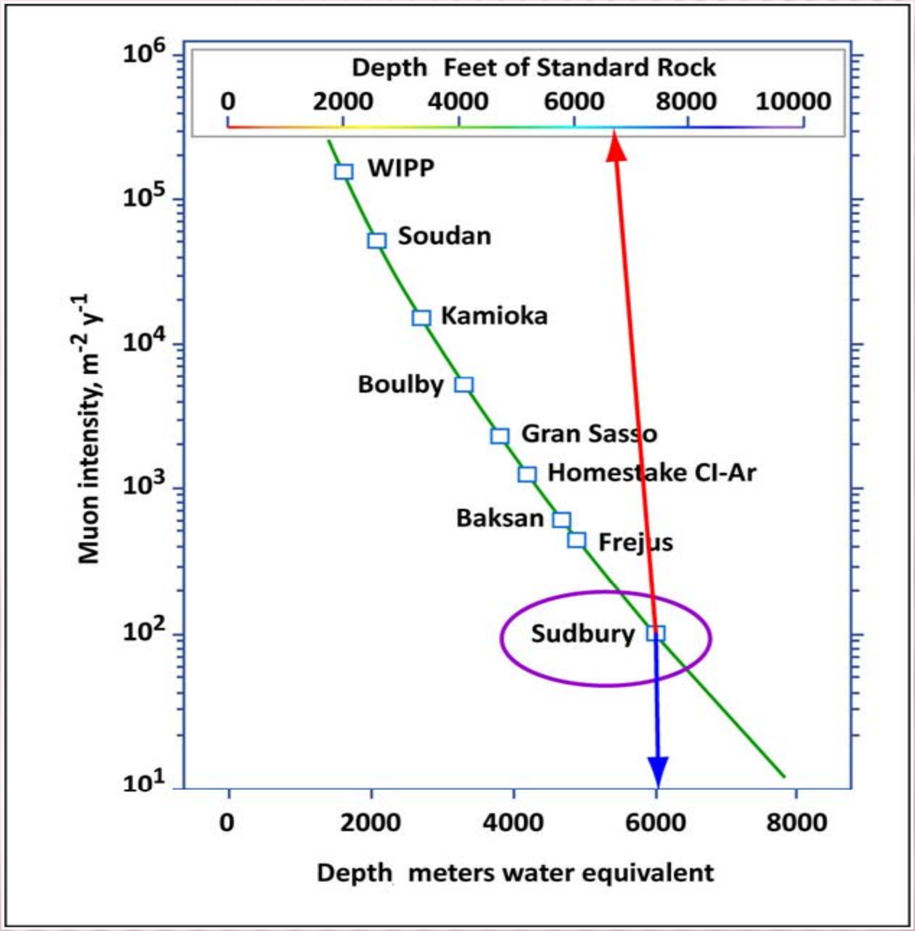
SNO Location: 46º 28' 30" N, 81º 12" 04" W in the INCO, Ltd International Nickel Company of Canada Creighton Mine , Sudbury, ON, Canada

Cosmic ray Intensity reduction with depth
SNO Detector Location

Location Depth 2092 m or 6800'

Over burden meter water equivalent ~ 6010

Ref.
The Sudbury Neutrino Observatory,
The SNO Collaboration, Nuclear Instruments and Methods in Physics Research A449 (2000) pp. 172-207.



http://arxiv.org/PS_cache/nucl-ex/pdf/9910/9910016v2.pdf

http://www.sno.phy.queensu.ca/sno/papers/nim_paper_99.pdf

SNO Detector Details

SNO detector was a heavy-water Cherenkov detector designed to detect neutrinos produced by fusion reactions in the sun.

SNO Location: 46° 28’ 30’’ N, 81° 12’’ 04’’ W in the INCO, Ltd

International Nickel Company of Canada

Creighton Mine , Sudbury, ON, Canada

Location Depth 2092 m or 6800’

Over burden meter water equivalent ~ 6010 mwe

Detector medium 1000 tonnes D_2O

Detector medium holder 12 m diameter Acrylic Vessel

Geodesic support structure 18 m diameter;

PMTs 9600 (~60% photocathode coverage)

Inner shielding H_2O 1700 tonnes

Outer shielding H_2O 5300 tonnes

Urylon liner radon seal

Ref.: The Sudbury Neutrino Observatory

The SNO Collaboration

Nuclear Instruments and Methods in Physics Research A449 (2000) pp. 172-207

http://arxiv.org/PS_cache/nucl-ex/pdf/9910/9910016v2.pdf

http://www.sno.phy.queensu.ca/sno/papers/nim_paper_99.pdf

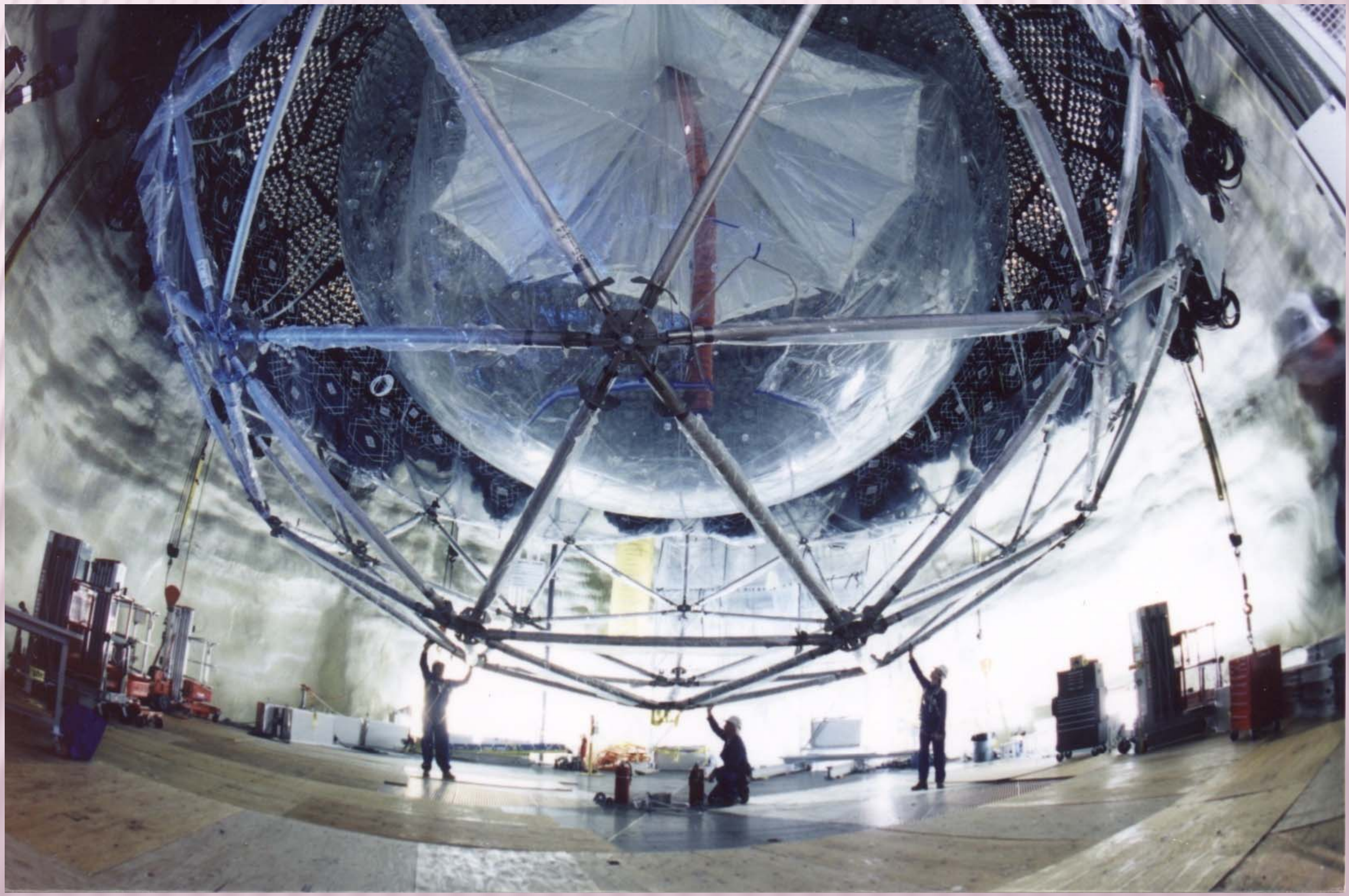
SNO Detector Details

Image of SNO detector
http://www.sno.phy.queensu.ca/sno/images/publicity_photos/index.html

For images of the SNO antineutrino detector components, visit the SNO image gallery
http://www.sno.phy.queensu.ca/sno/images/

SNO Detector Support Structure

SNO Detector during construction SNO3.jpg
Photo courtesy of SNO
http://www.sno.phy.queensu.ca/sno/images/publicity_photos/index.html



SNO Event Display

See the computerized reconstructed event display at

http://www.hep.utexas.edu/sno/

- **Sudbury Neutrino Observatory (SNO) Research Group, University of Texas at Austin High Energy Physics Lab**

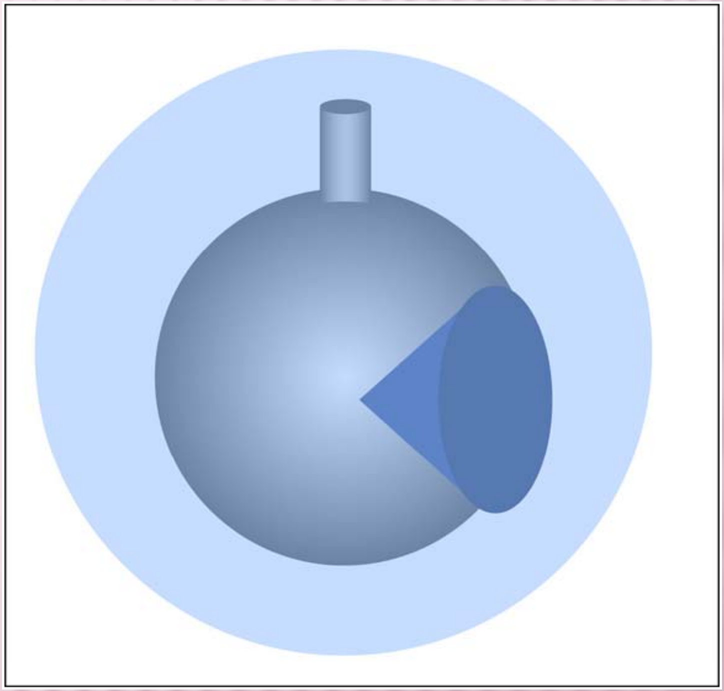


Figure. Pictorial concept of generation of a cerenkov radiation signal in conical form (shown in dark blue color),
Figure by MIT OpenCourseWare

SNO Event Display

http://www.sno.phy.queensu.ca/sno/events/xsnoed.html

- XSNOED (X-windows SNO Event Display) is a graphical display tool written for SNO by Phil Harvey of Queen's University. It is used by SNO collaborators to display live events in real time or stored events from file.
- In one of the three types of reactions for neutrinos in the SNO detector, a neutrino scatters off of an electron in the heavy water, and the energized electron produces a tiny light flash in the form of a (Cherenkov) cone of photons which reach about 60 to 150 of SNO's 10,000 light sensors, arranged on the surface of a sphere outside the heavyw ater.
- The sensor signals are analyzed to give the neutrino's direction of travel, and precise point and time for the interaction

Detecting AntiNeutrinos with SNO

- Inverse beta reaction:

$\bar{\nu}_e + d \rightarrow e^+ + n + n - 4.03$ MeV.

- Coincidence signal

The distinctive signature of a positron in coincidence with two neutrons allows SNO to detect antineutrinos with very low background.

By means of (n, n)-coincidence detections, SNO has sensitivity to antineutrinos with energies above the reaction threshold of 4.03 MeV.

- Reaction threshold: 4.03 MeV.

SNO Detector
Antineutrino Studies

Reference:

Electron antineutrino search at the Sudbury Neutrino Observatory,

SNO Collaboration,

Physical Review D, 2004, vol. 70, 093014, pp. 1-8.

http://arxiv.org/PS_cache/hep-ex/pdf/0407/0407029v1.pdf

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

Session 3 Summary

In this session, features of the existing well established antineutrino detector, KamLAND of Japan and neutrino detector, SNO of Canada are reviewed.

The major differences between KamLAND and SNO are:

1) Difference between the detection media for inverse beta-decay reaction

For SNO, inverse beta-decay reaction takes place between incident antineutrinos and the target deuterons . Because, the threshold energy of the detector is 4 MeV for this reaction, the antineutrinos originating in the radioactive decay of the K, U, Th (HPE) of the Earth are not detectable with high sensitivity like KamLAND.

For KamLAND, inverse beta-decay reaction takes place between the incident antineutrinos and the target protons. Because, the threshold energy of the detector is 2 MeV for this reaction, the antineutrinos originating from the K of the Earth are not detectable, but those from U and Th are detectable.

Session 3 Summary continued

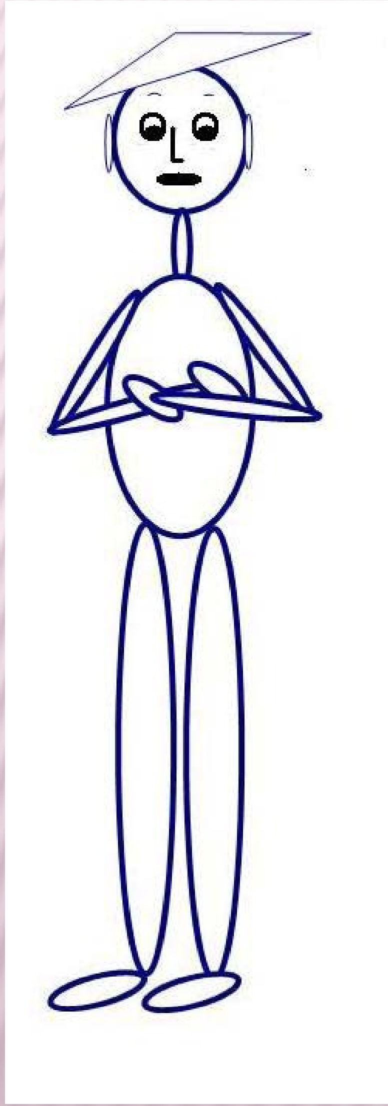
2) Difference in the detection methodology :

- SNO – Used Cherenkov radiation detection methodology for solar neutrino detection. This methodlogy retains the directional information of the incident radiation. The SNO detector detected the direction of the "Sun" by this methodology to discriminate neutrinos coming from all other directions.
- KamLAND – optimized for the neutrino oscillation studies using the fission reactor antineutrinos; the signal from reactor antineutrinos is major source of background interference to the signal from antineutrinos from the HPE of the Earth, when used for this purpose.

Session 3 Summary continued

- Therefore the data from these existing large antineutrino detectors is relevant for probing the HPE in the Earth's interior. This is only a first step, because the se detectors wer not built bult for HPE studies. We need dedicated detectors optimized for studying the HPE concentrations in the interior of the Earth all the way to the core.

Session Overview



- **Antineutrino analysis for concentration determination of the Heat Producing Elements (HPE) in the entire Earth, is for the purpose of determining the global radioactivity.**
- **This session provides features of the existing antineutrino detector s.**

  They are not dedicated to the concentration determination of HPE.

Session 3: Student Assignments January 20, 2010

1.

Read:

Short history of concept of Earth as antineutrino source (1960 – 2004), radiogenic heat sources inside the Earth

G. Domogatsky, V. Kopeikin, L. Mikaelyan, V. Sinev, 2004

http://arxiv.org/PS_cache/hep-ph/pdf/0409/0409069v2.pdf

Write: Summarize your understanding in at least one page.

Session 3: Student Assignments
January 20, 2010

2.

Read:

KamLAND reference article or web site.

SNO reference article or web site.

Write:

What is your understanding of the major differences between the two detectors for antineutrino analysis of K, U, Th in the Earth. Write at least one page.

References

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  Earth as a source of antineutrinos,
  Physical Review D, 1981, 23, 1116 – 1117.

- Boardman, R. J. (1992),
  The detection of Cerenkov radiation from neutrino interactions,
  http://www.sno.phy.queensu.ca/boardman_phd.pdf

- Domogatsky, G., V. Kopeikin, L. Mikaelyan, V. Sinev,
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  http://arxiv.org/PS_cache/hep-ph/pdf/0409/0409069v2.pdf
  12 Nov 2004.

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  http://arxiv.org/PS_cache/arxiv/pdf/0707/0707.3203v2.pdf
  18 Aug 2007.

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  Nature, 28 July 2005, 436, p. 499-503 | doi:10.1038
  http://www.nature.com/nature/journal/v436/n7050/abs/nature03980.html

- Kobayashi, M., Fukao, Y.,
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  Geophysical Research Letters,
  April 1991, vol. 18, no.4, p. 633-636.

- Krauss, L. M., S.L. Glashow, D.N. Schramm,
  Antineutrino astronomy and geophysics,
  Nature, 1984, 310, p. 191–198.

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  Measuring the Global Radioactivity in the Earth by Multidetector Antineutrino Spectroscopy
  Physical Review Letters 19 January 1998, vol. 80, no. 3, pp. 635-638.

- Rothschild, C. G., M.C. Chen, F.P. Calaprice,

  Antineutrino geophysics with liquid scintillator detectors,

  Geophysical Research Letters, April 1, 1998, Vol.25, No. 7 pp. 1083-1086.

  http://arxiv.org/PS_cache/nucl-ex/pdf/9710/9710001v2.pdf

- Suekane, F, T. Iwamoto, H. Ogawa,

  An Overview of the KamLAND 1-kiloton Liquid Scintillator

  http://arxiv.org/ftp/physics/papers/0404/0404071.pdf

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  The Sudbury Neutrino Observatory,
  Nuclear Instruments and Methods in Physics Research A
  2000, 449, pp. 172-207
  http://arxiv.org/PS_cache/nucl-ex/pdf/9910/9910016v2.pdf
  http://www.sno.phy.queensu.ca/sno/papers/nim_paper_99.pdf

- SNO Collaboration ,
  Electron antineutrino search at the Sudbury Neutrino Observatory,
  Physical Review D, 2004, vol. 70, 093014, pp. 1-8.
  http://arxiv.org/PS_cache/hep-ex/pdf/0407/0407029v1.pdf

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  http://www.nu.to.infn.it/exp/all/borexino

- Deep Ocean Anti-Neutrino Observatory
  neutrino.pd.infn.it/conference2007/Talks/Learned.ppt
  www.phys.hawaii.edu/~sdye/hanohano.htm
  http://arxiv.org/PS_cache/arxiv/pdf/0810/0810.4975v1.pdf

- EarTH
  Earth AntineutRino TomograpHy (EARTH)

www.phys.hawaii.edu/~jelena/post/hnsc/deMeijer_Hawaii-conf-2005.ppt

References

- GRAFG

  Geoneutrino Radiometric Analysis For Geosciences [GRAFG]

  http://www.lbl.gov/nsd/homestake/PDFs/dedc/july2008/DUSEL_Project_Update_Jun30_2008_GRAFG-ILA.pdf

  http://neutrino.lbl.gov/~dusel/HomestakeWorkshopApril2008/BioGeoEng/Ila_Geoneutrino.ppt

- LENA

  Low Energy Neutrino Astronomy detector

  http://arxiv.org/PS_cache/hep-ph/pdf/0610/0610048v1.pdf

  4 October 2006.

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- Massachusetts Institute of Technology,

  Cambridge, MA, USA
- The NORM Group Organization,

  Cambridge, USA and Guelph, Canada

is acknowledged.

END of Third SESSION

12.091 Basics of Analysis with Antineutrinos from Heat Producing Elements – K, U, Th in the Earth
January (IAP) 2010